

The Weather Riddle

All weather phenomena clouds, rain, snow, storms and cyclones occur within a narrow region of Earth's atmosphere called the troposphere. It is the Sun's heat that creates winds, clouds, cyclones and other weather phenomena. Sometime weather can also turn violent and cause widespread destruction of life and property. But modern space and computer technology has made it possible to track the paths of approaching cyclones and also issue advance flood warnings, thereby reducing loss of life considerably. In this book an attempt has been made to present an overview of the weather phenomenon and the various forces at work and to look at the various techniques used to make weather forecasts more reliable.

About the author

A retired scientist of the Council of Scientific and Industrial Research, Biman Basu is a former Editor of the popular science monthly *Science Reporter*. He has been a regular broadcaster over All India Radio for more than 30 years, has scripted several TV documentaries, and published more than 1,000 articles on popular science topics in various publications. He has 27 popular science books to his credit. Some of his books have also been translated into other Indian languages including Assamese, Hindi, Kannada, Marathi, Oriya, Punjabi, Tamil and Urdu and have gone into multiple reprints. He is a winner of the 1994 NCSTC National Award for Science Popularisation, awarded annually by the Department of Science and Technology.

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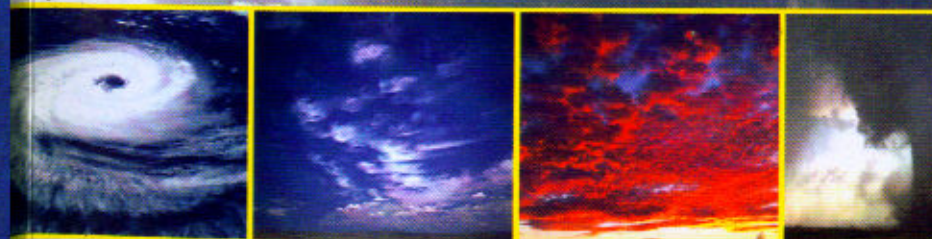
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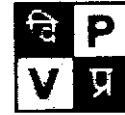
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Foreword

Earth is the only planet we know of with life on it. Animals, Plants and microorganisms maintain a delicate balance with a variety of life forms we call Biodiversity. Each species depends on other species for its existence. When we talk of life on earth, we also talk about the human species. If we need to understand and preserve our environment, we shall need to understand the interdependence of the species on each other and the importance of natural resources like air, water and soil for living beings.

Life has continued to evolve on this earth over millions of years adapting to changing environment. Only those species have survived that have adapted to the changing environment. This change could be due to natural causes like earthquakes, eruption of volcanoes, cyclones, and so on. It even could be due to climate change. However, quite often this change is brought about by the species higher up in the ladder of evolution that tries to control environment to suit its needs and for development. This is precisely what human species has done to our fragile planet.

We need energy for development; which we traditionally obtain by burning natural resources like

firewood, coal and petroleum. This is what we have been doing for centuries. Today there is consensus that human activities like burning of fossil fuels and consequent pumping of gases like carbon dioxide into atmosphere have been responsible for the earth getting hotter and hotter. Today, there are threats to our planet arising from climate change, degrading environment, the growing rate of extinction of species, declining availability of fresh water, rivers running dry before they can reach sea, loss of fertile land due to degradation, depleting energy sources, incidence of diseases, challenge of feeding an exponentially growing population, and so on. The human population is now so large that the amount of resources needed to sustain it exceeds what is available. Humanity's environmental demand is much more than the earth's biological capacity. This implies that we are living way beyond our means, consuming much more than what the earth can sustain.

To draw the attention of the world to these aspects and in an attempt to establish that environment is where we live; and development is what we all do in attempting to improve our lot, within that abode, the United Nations has declared the year 2008 as "The Year of the Planet Earth". It is hoped that with the cooperation of all we shall be able to save the biodiversity and the life on this planet. A host of activities and programmes are being organized all over the world for this purpose. One of the important aspects is to make people aware about the challenges we face and the possible solutions to save this planet from heading towards catastrophe. It is with such thoughts that Vigyan Prasar has initiated programmes with activities built around the theme "The Planet Earth". The activities comprise of

development and production of a series of informative booklets, radio and television programmes, and CD-ROMs; and training of resource persons in the country in collaboration with other agencies and organizations.

It is expected that the present series of publications on the theme "The Planet Earth" would be welcomed by science communicators, science clubs, resource persons, and individuals; and inspire them initiate actions to save this fragile abode of ours.

Vinay B. Kamble
Director, Vigyan Prasar
New Delhi

Preface

Weather plays a big part in our lives. It affects many of the things that we do, from the clothes we wear and the food we eat, to where we live and how we travel. No wonder, therefore, the weather is of great interest to people everywhere, from meteorologists – the scientists who study it in great depth – to every one of us in our everyday lives. Weather lore has been around in almost every culture since people needed to predict the weather and plan their activities.

All weather phenomena – clouds, rain, snow, storms, and cyclones – occur within a narrow region of Earth's atmosphere called the troposphere that extends from ground level up to about 16 kilometres. It is the Sun's heat that creates winds, clouds, cyclones, and other weather phenomena. Sun's heat absorbed by the Earth produces air currents, which influence evaporation of ocean water, forming clouds and rain, which then adds to vast rivers that constitute the water cycle.

Weather is also decided by the Earth's wind systems. When the Sun warms the air, the air expands, gets lighter, and rises. Cooler, heavier air moves in from surroundings to fill the void created by the rising warmer air. Thus wind

usually blows from areas of high air pressure to areas of low pressure. Humid air being lighter than dry air, it produces low-pressure areas that often experience rain and unsettled weather.

Weather can also turn violent and cause widespread destruction of life and property. Modern space and computer technology has made it possible to track the paths of approaching cyclones and also issue advance flood warnings, thereby reducing loss of life considerably. Weather forecasting techniques have also undergone sea change and it is now possible to make reliable forecasts of up to seven days in advance.

In this book an attempt has been made to present an overview of the weather phenomenon and the various forces at work, and to look at the various techniques used to make weather forecasts more reliable.

I am grateful to Dr. V.B. Kamble and Shri B.K. Tyagi for giving me the opportunity to write this book. I am also indebted to Shri Pradeep Kumar for making an excellent job of page layout for the book.

Biman Basu

New Delhi
1 November 2007



Weather in Our Life

Weather is undoubtedly one of the most common topics of conversation every day be it summer, winter or rain. We seem to be too much preoccupied with the daily weather. It is too hot or too cold; too sultry or too windy. Of course, we do have pleasant weather during spring and autumn. But what is this 'weather' we keep talking about?

The *Oxford English Dictionary* defines weather as 'the condition of atmosphere at a certain place and time, with reference to the presence or absence of sunshine, rain, wind, etc.' When we talk about weather, we are really talking about the air, or the atmosphere at any place. Weather is what the atmosphere is like in any one place at any one time – whether it is warm or cold, wet or dry, and how cloudy or windy it is, for example. The weather is made up of several components, which are nothing but individual physical features of the atmosphere. At a given locality, at least seven such components may be observed at any one time. These are: temperature, humidity, wind, pressure, visibility, clouds, and precipitation; that is, rainfall or snow. On any single day we will find the weather to be different at different places. For example, in deserts, it very rarely rains. In tropical jungles, it

is always hot and steamy. Even at one place the weather does not remain the same throughout the day; it keeps changing all day. It may be cool and pleasant in the morning, sultry in the afternoon followed by rain in the evening and then pleasant weather again – all in the span of a single day.

Weather plays a big part in our lives. It affects many of the things that we do, from the clothes we wear and the food we eat, to where we live and how we travel. No wonder, therefore, the weather is of great interest to people everywhere, from meteorologists – the scientists who study it in great depth – to every one of us in our everyday lives. Farmers and horticulturists look up to favourable weather in expectation of bumper crops. If the temperature or rainfall deviates from the normal the result is often disastrous. Civil aviation depends heavily on weather. Bad weather often leads to delays or cancellation of flights resulting in not only inconvenience to passengers but also financial loss. Most of us know how rain plays spoilsport, disrupting cricket matches, often at the most crucial stage. It is also the weather that brings miseries to hundreds of thousands in the form of floods, droughts, and cyclones.

Weather lore

Over the ages, sailors, fisherman, farmers, and shepherds learned to look at weather signs to try and predict the weather. Weather lore has been around in almost every culture since people needed to predict the weather and plan their activities. Sailors and farmers relied on it to navigate ships and plant crops. Some weather lore concerning the appearance of the sky, the conditions of the atmosphere, the type or movement of the clouds and the direction of the winds have a scientific basis and likely can predict the weather. But much of the weather lore is just myth, with no scientific basis.

One of the earliest weather folklore comes from 4th century BC, when the Greek philosopher Theophrastus wrote:

If ants on the side of a hollow carry their eggs from the nest to the high ground, it indicates rain.

This holds true even today. We can indeed predict rain by watching ant movement. Just before rain rows of ants can be seen carrying eggs leaving their nests and scurrying to higher grounds.

Here are a few more samples of weather lore that have a scientific explanation, which is also given.

*When the dew is on the grass,
Rain will never come to pass.
When grass is dry at morning light,
Look for rain before the night.*

Dry air produces high pressure, which also allows for rapid cooling at night in autumn or winter, resulting in the formation of dew early in the morning. But moist air being lighter rises and produces low pressure, which prevents the development of morning dew. A low pressure usually brings rain.

*The gnats bite and I scratch in vain,
Because they know it is going to rain.*

This is true because flying insects fly closer to the ground before the rain. Also the drop in density of the air before the rains irritates them, causing them to swarm more and to bite more diligently.

*Ring around the Moon,
Rain will fall soon.*

When a ring is seen around the Moon it means moonlight is passing through thin cirrus clouds, which are usually made up of fine ice crystals. If cirrus clouds are seen along with a falling barometer (low pressure), it usually indicates approach of rain clouds.

*Sound travelling far and wide,
A stormy day will betide.*



Ring around the Moon is formed by moonlight passing through thin cirrus clouds, which are usually made up of fine ice crystals.

The speed at which sound travels depends largely on the density of the air through which it travels. Usually rain is associated with moist air, which has less density than dry air. This density change causes sound waves to travel differently, usually farther than normal. Occasionally, the sound of a distant passing train can be heard only before the arrival of rain.

*When clouds appear like rocks and towers,
The earth's refreshed with frequent showers.*

The characteristic cauliflower shape of cumulus clouds during the monsoon months is an indicator of moist surface air rising quickly into cooler, drier air aloft. These clouds grow upwards like towers and cause thundershowers and lightning.

*Red sky in morning, sailor's warning.
Red sky at night, sailors' delight.*

When we see a red sky at night, this means that the setting Sun is sending its light through a high concentration of dust particles. This usually indicates high pressure and stable air coming in from the west, and good weather. But a red sunrise reflects the dust particles of a storm system that has just passed from the west. If the morning sky is a deep fiery red, it means high water content in the atmosphere, indicating possibility of rain.



Our Restless Atmosphere

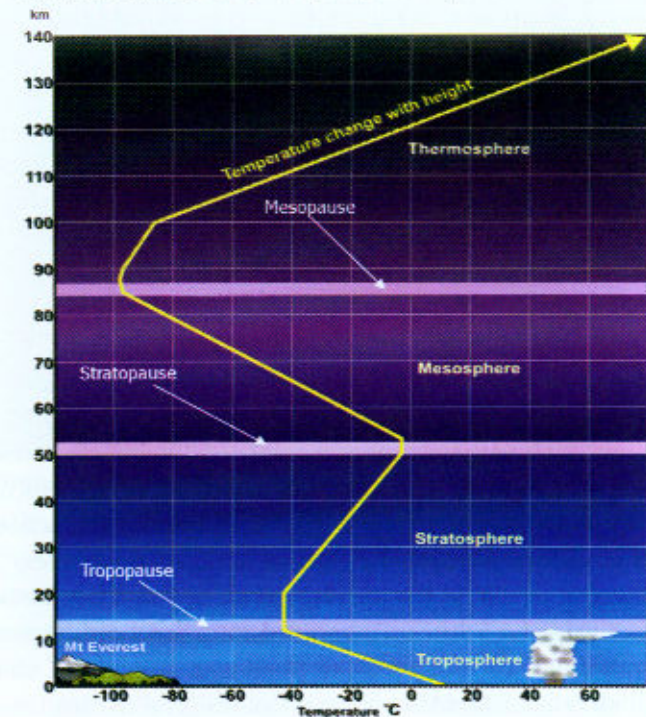
The weather depends to a large extent on the happenings in the Earth's atmosphere. It is the atmosphere where all weather phenomena – clouds, rain, snow, storms, and cyclones occur. When we look up at the sky from ground we actually look through the atmosphere, which covers the Earth like a blanket. The atmosphere is basically a mixture of gases. More than three quarters of the atmosphere is made up of nitrogen and most of the rest is oxygen. But it is the remaining 1%, a mixture of carbon dioxide, water vapour and ozone that not only produces important weather features such as cloud and rain, but also has considerable influence on the overall climate of the Earth, through mechanisms such as the greenhouse effect and global warming. The amount of water vapour in the atmosphere varies widely from place to place and from season to season at the same place. The air over deserts is almost bone dry, with only occasional traces of water vapour, while the air in tropical forests almost always remains saturated with water vapour.

If we go up from ground level we will find that the atmosphere thins out – it becomes less and less dense. The amount of oxygen in the air also drops with height and at a

height of a few kilometres the oxygen level may go down to only a third of the level at ground level. That is why we feel breathless if we go to places like Rohtang Pass in Himachal Pradesh or Leh in Ladakh, which are situated at heights of over 3,500 metres. Mountaineers often have to carry oxygen cylinders to support breathing when climbing heights of more than 8,000 metres, although a few daring climbers have made it to the top of Mount Everest (8,850 metres) without oxygen.

The layers of atmosphere

Scientists divide the Earth's atmosphere into five layers each of which has a peculiar characteristic. The layer closest to the Earth is called the 'troposphere', which extends from



Earth's atmosphere is roughly divided into five layers each of which has a peculiar characteristic.

ground level up to 16 kilometres from the sea level. The height of the troposphere at the equator is the highest due to the amount of solar energy reaching Earth. It is the lowest at the two poles. All the weather phenomena such as clouds, rain, snow, storms, lightning and thunder occur only in this layer because it is this layer that contains most of the water vapour. In fact most of the weather-related phenomena are determined by the way water changes in the air, and so without water there would be no clouds, rain, snow, or other weather features. In the troposphere temperature drops 1°C every 165 metres. The level at which temperature stops decreasing is called the tropopause. Temperatures there can be as low as -58°C .

The troposphere is not static – it is an unstable layer where the air is constantly moving. In fact, at times it is the most turbulent layer of the atmosphere. As a result, passengers in aircraft flying through the troposphere, especially during the rainy season, often have a very bumpy ride. Because of this turbulence, most jet airliners fly higher in the stratosphere where the air is more still and clear and they can fly above the clouds.

Above the troposphere lies the 'stratosphere', which extends to a height of about 50 kilometres. Temperature here increases to about 4°C . In the stratosphere there is virtually no up and down movement of air. That is why the layer of ozone gas found in this layer at a height of about 24 kilometres does not dissipate away. The ozone is produced here by the action of ultraviolet radiation from the Sun on oxygen molecules. The ozone layer is crucial to the survival of all life on Earth because it filters out much of the Sun's harmful ultraviolet radiation that would otherwise be dangerous to plant and animal life.

Beyond the stratosphere, the part of the atmosphere between 50 and 80 kilometres above the Earth's surface is

known as the 'mesosphere'. Here the temperature decreases again. Temperatures stop decreasing at the mesopause which is the region in between the mesosphere and the next layer, the 'thermosphere', which lies between 80 and 500 kilometres above the sea level.

In the thermosphere the temperature rises steadily with height, heated by intense solar radiation. Temperatures here can be as high as about $1,480^{\circ}\text{C}$ under certain conditions. Space shuttles fly in this region and it is also where the polar lights



Auroras are luminous atmospheric phenomena that generally appear as bright colourful bands of light in the Polar Regions.

or auroras are seen. The thermosphere is also the region where layers of electrically charged particles called ions are found. These layers, collectively known as the 'ionosphere', play a crucial role in long-distance radio communication as they can reflect radio waves of certain wavelengths back to Earth.

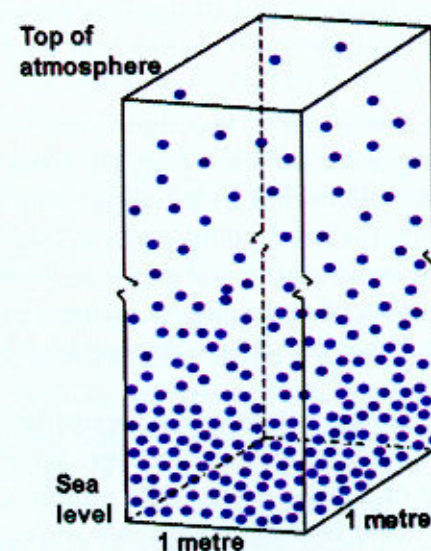
Auroras, also commonly referred to as the southern and northern lights, are a luminous atmospheric phenomenon that generally appear as bright colourful bands of light in the Polar Regions. Auroras are caused by charged high-energy particles from the solar wind that are trapped within the magnetic field of the Earth. The bright visually pleasing colours commonly associated with auroras are the result of electrons colliding with oxygen and nitrogen molecules in the Earth's atmosphere. As these molecules become energized and then return back from their energized state, they emit visible light that can be seen by the naked human eye. This is very similar to the way light is produced in neon tubes where neon atoms energised by electrons give off red light.

The region of the atmosphere beyond the thermosphere is known as the 'exosphere' where the atmosphere merges into the emptiness of space. Satellites in low Earth orbits are placed in this region, which lies between heights of 500 and 1,000 kilometres. This layer consists of a variety of very small quantities of gases including helium, nitrogen, oxygen and argon. Temperatures here can range from 300°C to 1,650°C.

Air pressure

We have seen above, the atmosphere extends up to a height of about 1,000 kilometres. If we consider a column of air 1,000 kilometres tall the total amount of gases in the column would be pretty large and so would be pressure the column would exert at the ground level. These gases press down on the Earth's surface, exerting a force that we call atmospheric pressure or air pressure. Although we are usually unaware of this pressure, it actually presses down very hard. Every square metre column of air at sea level weighs more than 10 tonnes – roughly equivalent to the force of an elephant balancing on a desk!

Of course, air pressure changes over time and from place to place. It depends on many factors, such as the height of a place, temperature, and amount of moisture. For example, if we go up a mountain, the air pressure drops constantly. At greater heights, the air pressure is lower, because there is less air above weighing down. This can be compared to the weight of a pile of blankets. If 1,000



Air pressure falls with height because there is less air molecules above weighing down.

blankets are piled up one above the other the total weight at the bottom of the pile will be substantial. Air pressure at sea level is the equivalent of having many blankets, which would feel very heavy. But if we take only one blanket, which is like going to the top of a mountain, the total weight of the blanket will be much less. If we go still higher – above the height of mountains and into the stratosphere, the pressure will decrease until it reaches about zero, as here there is hardly any air above.

Air pressure also depends on the amount of water vapour present. Moist air is lighter than dry air and hence exerts less pressure. Most people find it hard to believe that humid air is lighter, or less dense, than dry air. How can the air become lighter if we add water vapour to it? The answer is quite simple and scientists have known it for a long time. The first was the English physicist Isaac Newton, who stated that humid air is less dense than dry air in 1717 in his book, *Optics*. But other scientists did not generally understand this until later in that century.

To see why humid air is less dense than dry air, we need to turn to one of the laws of nature the Italian physicist Amadeo Avogadro discovered in the early 1800s. In simple terms, he found that a fixed volume of gas, say one cubic metre, at the same temperature and pressure, would always have the same number of molecules no matter what gas is in the container. Most chemistry books explain how this works.

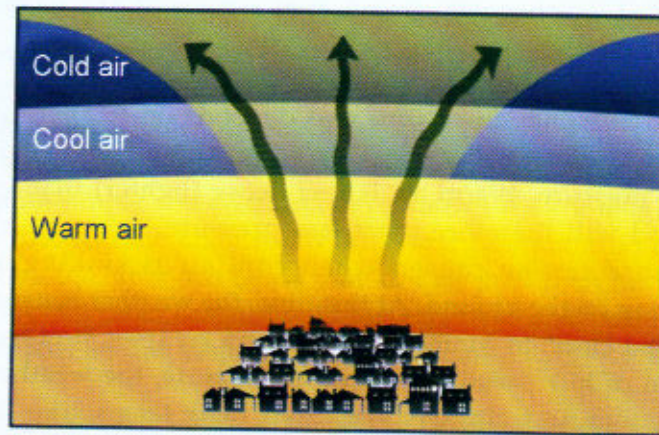
Now imagine a cubic metre of perfectly dry air. It contains about 78% nitrogen molecules, which have a molecular weight of 28 (two atoms with atomic weight 14). Another 21% of the air is oxygen, with each molecule having a molecular weight of 32 (two atoms with atomic weight 16). Water molecules have a molecular weight of 18 (one oxygen atom with atomic weight of 16, and two hydrogen atoms each with atomic weight of 1). Thus a molecule of water is lighter than both nitrogen and oxygen. So, if we replace nitrogen and oxygen with water vapour it will decrease the net weight of the air in the cubic metre; that is, its density would decrease and it would exert less pressure. Hence the larger the amount of water vapour present in air the lesser pressure will it exert on the ground compared to the pressure exerted by dry air. That is why in the atmosphere water vapour-rich air marks low pressure areas, which often bring

unsettled weather and rain whereas regions of dry air mark fair weather areas.

Atmospheric pressure also depends on temperature. Cool air is denser (heavier) than warm air and hence exerts more pressure. Warm air is less dense (lighter) than cool air and will therefore exert less pressure. Areas of high pressure can be caused when cool air is sinking and pressing on the ground. At this time, the weather is usually dry and clear. In contrast, when warm air rises, it causes a region of low pressure. With low pressure, the weather is often wet and cloudy. We often hear terms like 'low pressure' and 'deep depression' in weather bulletins, which forecast heavy rainfall and bad weather.

Inversion

Normally, within the lower atmosphere (the troposphere) the air near the surface of the Earth is warmer than the air above it, largely because the atmosphere is heated from below as solar radiation warms the Earth's surface, which in turn then warms the layer of the atmosphere directly above it. We have seen earlier, in the troposphere temperature drops 1°C every 165 metres; that is, it becomes cooler as we go up. That is why mountain tops are always cooler than the plains below. But there are times, especially in winter, when just the opposite happens – the temperature rises with height near the ground. When this happens, a layer of warm air lies over cool air near the ground and acts like a 'lid'. As a result pollutants like oxides of nitrogen and sulphur, and smoke that under normal conditions rise up and dissipate, are trapped close to ground leading to damaging environmental conditions like 'smog', which causes irritation to eye and throat. This condition, known as 'temperature inversion', often poses a serious health hazard, especially for those with breathing problems.



Normally temperature drops with height which makes pollutants and smoke rise and dissipate (top). When there is inversion the temperature rises with height near the ground. When this happens, a layer of warm air lies over cool air near the ground and acts like a 'lid', trapping pollutants under it (bottom).

Thus everything that constitutes weather is present in our atmosphere. But merely the presence of air and water vapour in the atmosphere does not produce weather. There is a driving force that brings about the changes producing the various weather phenomena. Let us see what drives the weather engine.

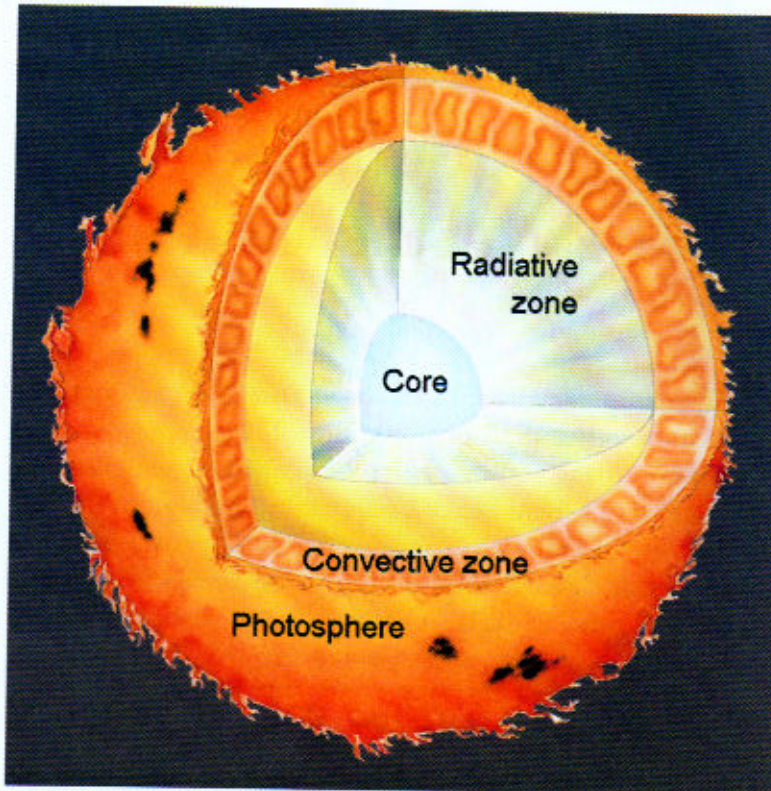


Sun: The Weather Maker

The energy source that drives the Earth's weather engine is none other than our own Sun. Life itself would not exist without the steady source of heat and light from the Sun, nor would there be coal, oil, plants, wind, and rain. It is the Sun that decides whether the air is hot or cold, windy or calm, wet or dry, clear or cloudy. It is the Sun's heat that creates winds, clouds, cyclones, and other weather phenomena.

As we know, the Sun is actually a star – a medium-sized star – and is the source of all energy on Earth. The core of the Sun consists of mainly hydrogen, the lightest element. In the core, hydrogen atoms undergo thermonuclear fusion – hydrogen nuclei fuse together at extremely high temperature – to produce helium atoms. In the process enormous amounts of energy are released that the Sun radiates and we receive in the form of heat and light on Earth. Almost every activity on Earth depends on a regular supply of Sun's heat and light. Without sunlight no plants can grow and without plants no animals or humans can survive. Even our energy sources are

indirectly products of the Sun. The fossil fuels – coal, oil, and gas – are remains of past living organisms and plants that were sustained by the Sun millions of years ago. Absence of sunlight, even for a year or so can wipe out several species,

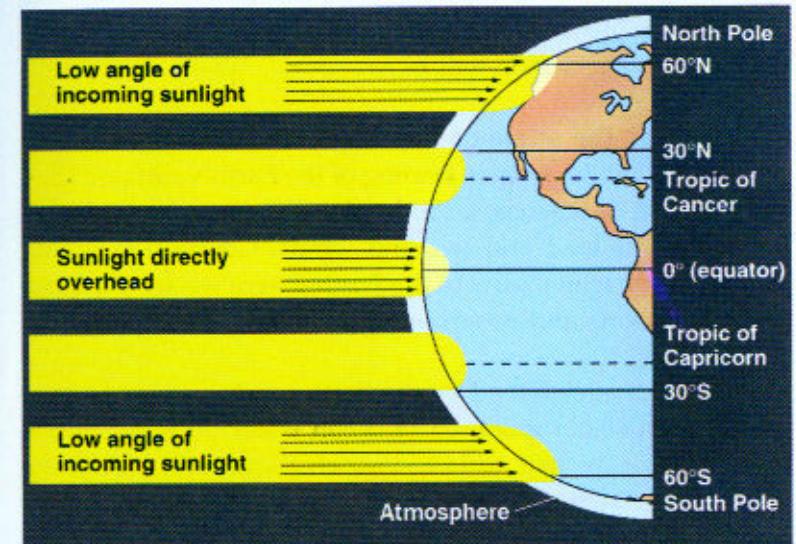


In the core of the Sun hydrogen atoms undergo thermonuclear fusion – hydrogen nuclei fuse together at extremely high temperature to produce helium atoms and giving off enormous amounts of energy which is radiated away.

as is supposed to have happened 65 million years ago when a giant asteroid hit the Earth that produced a thick blanket of dust and ash cutting off sunlight, leading to the extinction of dinosaurs and many other species.

Uneven heating of the Earth

Since the Earth is shaped like sphere and it rotates on an axis that is tilted at an angle to the plane of Earth's orbit, not all parts of the globe receive the same amount of sunlight throughout the year. As a result, near the equator the temperatures always remain high. As we go to higher latitudes – towards north or south – the conditions become more



The intensity of sunlight falling on Earth's surface depends on the latitude.

pleasant and the temperatures moderate. As we cross the polar circles, the condition becomes frigid, with temperatures dropping below zero.

The latitude or the distance from the equator plays an important role in deciding the weather of place – in general, nearer the equator the higher the average temperature of a place would be and the further from it the cooler would it become. As we go nearer the poles the temperature drops sharply, which in winter may fall tens of degrees below zero. The weather on

mountains often change unpredictably, brought about by sudden changes in wind direction and cloud formation.

When the Sun heats an air mass it expands and becomes lighter. The warm air mass then rises due to convection and an area of low pressure is created. Elsewhere, as cold air sinks, an area of high pressure is created. Then air from high-pressure areas moves into low-pressure areas to balance out. This movement is what we see as wind. The greater the difference in pressure or temperature between these two areas the stronger the winds will blow.

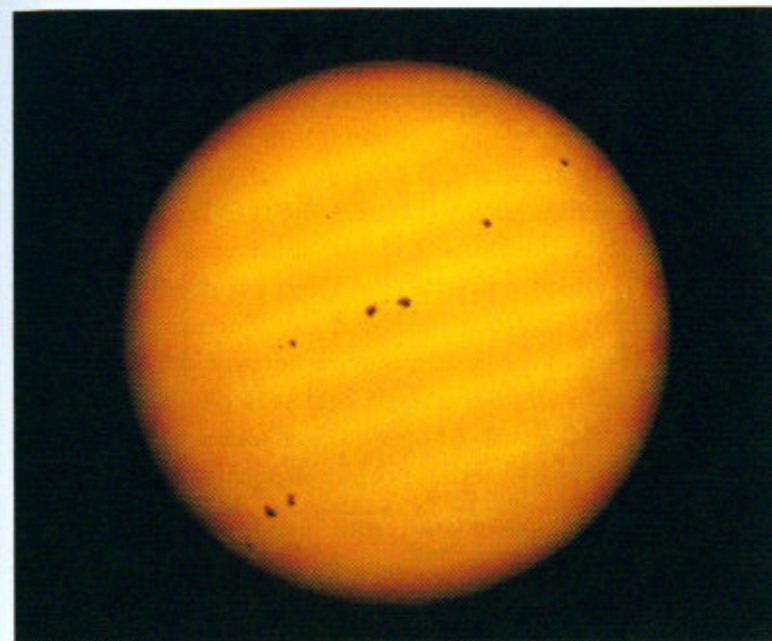
Besides the angle of the Sun, there are other factors responsible for the uneven heating of the Earth's surface. They are the cycle of seasons, latitude, cloud cover, re-radiation of heat from the land and sea, and winds. Convection occurs more in the warmer parts of the Earth where we see the more frequent storms and rough weather.

Sun's heat absorbed by the Earth produces air currents, which influence evaporation of ocean water, forming clouds and rain, which then adds to vast rivers that constitute the water cycle. When the Sun heats the oceans water vapour forms and rises. As the vapour rises it expands and cools and the moisture in it condenses into tiny water droplets – forming clouds. Normally constant upward draughts of air keeps the clouds afloat. But when the cloud is of the right type, with sufficient moisture, and conditions suitable for rain, the tiny droplets coalesce and form larger droplets that fall to the ground as rain drops, pulled by gravity.

Sunspots and weather

Over the years, with the improvement in weather records, it has come to light that small changes in the output of Sun's energy caused by appearance of sunspots or disturbances on

the Sun may be influencing Earth's weather. Such a correlation was first recorded by Chinese astrologers more than a thousand years ago. In recent times an eleven-year cycle of sunspots, called the 'solar cycle' has been discovered, which appears to be linked to disturbances in the high atmosphere of the Earth such as auroras and radio blackouts. During the



The appearance of sunspots has been found to influence Earth's weather.

solar cycle the Sun goes from a minimum to a maximum period of activity represented by a peak in the number of sunspots and flare activity.

Sunspots are related to Sun's magnetism. In fact, sunspots always appear in pairs. If we could bury a giant horseshoe magnet beneath the surface of the Sun, it would produce a magnetic field similar to that generated by a sunspot pair. Records show that solar magnetism was quite high about 1,000

years ago for several hundred years, then dropped to very low levels, as it does every 300 years or so. Earth cooled when magnetism was low. In the past 20 years, NASA satellites have found a correlation between the Sun's magnetism and energy output, and changes in temperature on Earth. Data indicate that cloud cover is greatest when the Sun's magnetic field is least. Perhaps cosmic rays act as seed nuclei to change cloud cover a few kilometres above the Earth.

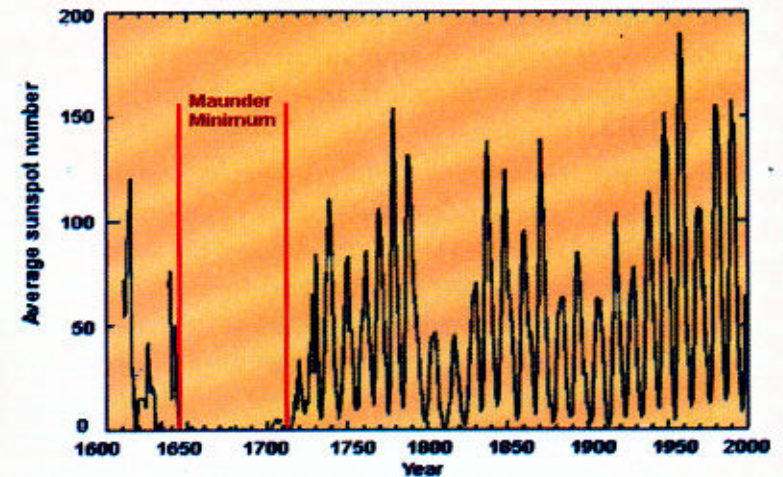
However, the energy output of the Sun varies very little over the solar cycle – it is less than 0.1% – and some scientists doubt whether such slight changes can really affect the troposphere of the Earth, where all the weather phenomena occur. But it is possible that the solar cycle affects the stratosphere, which amplifies the effect on Earth's weather. This possibility cannot be ruled out because the Sun's ultraviolet output varies 10 times more over the solar cycle than its overall radiation output, and it is plausible that the temperature of the stratosphere, where ozone is an efficient absorber of ultraviolet radiation, varies significantly with the solar cycle.

The Maunder Minimum

One suggestion of a link between sunspot and weather comes from historical records. There was a curious period of about 70 years shortly after the discovery of sunspots by the Italian astronomer Galileo Galilei, from about 1645 to 1715, when the Sun did not appear to have sunspots. This period is called the 'Maunder minimum' after the British astronomer Edward Walter Maunder, who first noted its existence from past records. Records also show that phenomena such as the aurora borealis (northern lights) that are associated with solar activity were also few during this period. The period is also linked with what has come to be known as the 'Little Ice Age' in

Europe and North America. During this period astronomers observed only about 50 sunspots over a 30-year period as opposed to a more typical 40,000-50,000 spots.

During the periods of low solar activity; that is, when the sunspot number is low, levels of the Sun's ultraviolet radiation decrease, which can significantly impact ozone formation in the Earth's stratosphere, which in turn can alter



There was a curious period of about 70 years, roughly from about 1645 to 1715, when the Sun did not appear to have sunspots. This period is called the 'Maunder minimum'.

the heating of the oceans. As a result, winter temperatures can drop as much as 1° to 2°C – enough to freeze rivers and alter agriculture, economy, etc. Based on this relationship scientists have been trying to work out a model to allow prediction of future changes in solar activity and its effects on Earth.

How does the Sun's influence on weather compare to that of increasing greenhouse gases through burning fossil

fuels? From weather records it is now clear that the 20th century was warmer than the 19th century. The past century's weather has had three major trends: a strong warming which peaked around 1940, a cooling trend until the late 1970s, and warming since then. It is now almost universally accepted that the increase in Earth's average temperature and anomalous weather in many parts of the world during recent decades is due to the accumulation of greenhouse gases in the atmosphere because of human activity, which is causing global warming. So, although the Sun plays a major role in determining weather, human influence may become a significant factor in future unless corrective action is taken to check global warming.

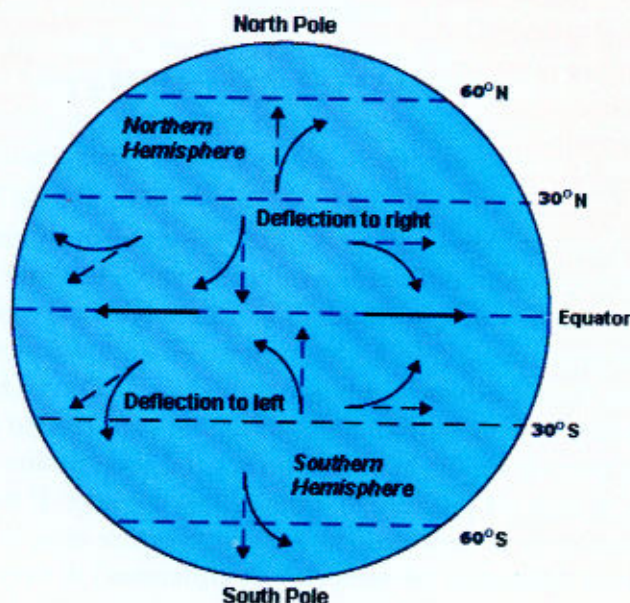


The Wind Systems

When air blows we call it wind. Winds form an essential component of Earth's weather system. The wind blows because air has weight. Cold air weighs more than warm air, so the pressure of cold air is greater. When the Sun warms the air, the air expands, gets lighter, and rises. Cooler, heavier air moves in from surroundings to fill the void created by the rising warmer air. Or, in other words, wind usually blows from areas of high air pressure to areas of low pressure. If the high pressure area is very close to the low pressure area, or if the pressure difference (or temperature difference) is very great, the wind can blow very fast. And the moving air can bring in moisture, rain-bearing clouds, and thunderstorms.

Since air is colourless and transparent, we cannot actually see the air moving. As we know, the strength of the wind can vary enormously. Sometimes air moves slowly and the wind is barely noticeable. When the weather is clear we may experience a gentle breeze, when the wind is still very light but we can feel it on our faces and in our hair, and we may hear leaves rustling. At other times, the air can move very quickly and become a gale or hurricane, blowing down trees and damaging cars and buildings.

Wind direction is always given from where it is coming and usually when we are talking about the wind it is the horizontal motion we are concerned about. When we say westerly wind of 10 to 20 kilometres per hour, it means horizontal wind blowing from the west at velocities of 10 to 20 km/h.



The spin of the Earth produces what is known as the 'Coriolis Effect', which changes the direction of wind blowing in a north-south direction.

Even when it blows horizontally, the speed at which the wind blows depends on height. For example, surface wind differs from cloud level winds because surface friction reduces the velocity. Horizontal wind is also influenced by the spin of the Earth due to what is known as the 'Coriolis Effect'. As a result the wind blowing in a north-south direction is bent to the right in the north of the equator and to the left in the

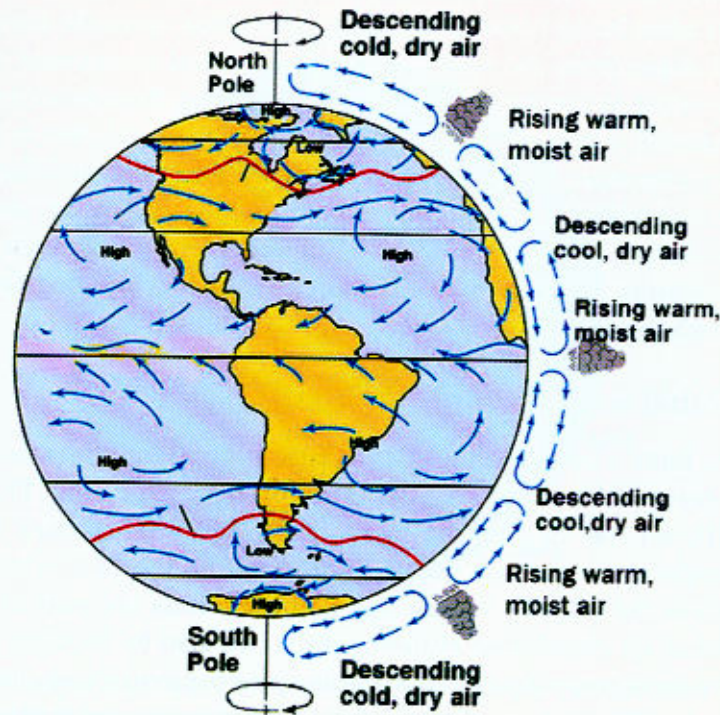
south. Because of these influences also horizontal wind near the surface is slowed down. When wind blows over the sea it causes waves; the size of the wave depends on the strength of the wind and the distance it has travelled over the sea.

In the atmosphere, wind sometimes blows in a vertical direction too, as happens in updrafts inside thunderclouds that often bring hailstorms. Wind also moves upwards along hill slopes from the valley below. The vertical component of the wind is typically very small (except in thunderstorm updrafts) compared to the horizontal component, but it is very important for determining the day to day weather. When air moves vertically upward it cools, often to saturation, and can lead to formation of clouds and rain. Downward moving air warms, causing evaporation of clouds and bringing fair weather.

Global wind pattern

We have already seen that different parts of the world receive different amounts of heat from the Sun. This differential heating in turn results in differences in temperature and air pressure around the world – which drives the world's winds. All of these winds are part of a global air circulation system, which can also be thought of as a mechanism by which the atmosphere moves excess heat around. That is, wind movements help in balancing the heat globally. All wind, directly or indirectly, helps to transport heat either away from the surface of the Earth, where sunlight causes an excess of energy build-up, or from warm regions (usually the tropics) to cooler regions (usually the higher latitudes). Extra-tropical cyclones accomplish much of this heat transport outside of the tropics, while in the tropics the trade winds, monsoons, and hurricanes transport much of the heat.

The global wind pattern makes air move between different areas around the world and also at different heights in the atmosphere. Colder air from the poles tends to sink and move towards the equator closer to the surface of the Earth. In contrast, warm air from the equator rises and moves



The global air circulation system is a mechanism by which the atmosphere moves excess heat around.

towards the poles high in the atmosphere because it is lighter. This creates cell-like patterns of wind around the world.

The wind pattern anywhere also depends on which side of the equator the wind is blowing. The trade winds are the

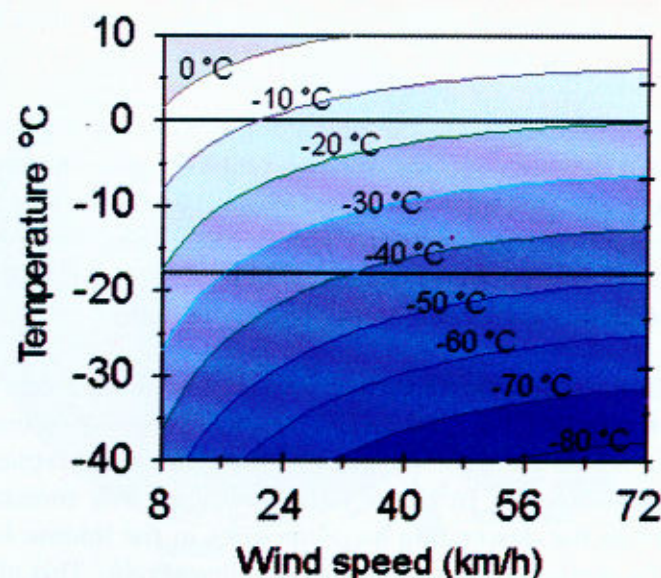
prevailing winds in the tropics that blow from regions of high-pressure in latitudes 30°N and 30°S towards the regions of low-pressure around the equator. Trade winds north of the equator blow from the northeast. South of the equator, they blow from the southeast. Their name derives from the Middle English 'trade', meaning 'path' or 'track,' and thus the phrase "the wind blows trade," that is to say, on track. When the trade winds of the two hemispheres meet near the equator, the air rises, and as the rising air cools, clouds and rain develop, which is characteristic of tropical climate near the equator.

The westerlies are the prevailing winds in the middle latitudes between 30° and 60°, which blow from the high-pressure area towards the poles. Westerlies blow from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere. These winds steer storms from west to east across middle latitudes.

Both westerlies and trade winds blow away from the 30° latitude belt, but over large areas centred at 30° latitude, surface winds are light. As the air blows away it is replaced by descending air from the surroundings. Any moisture present in the descending air evaporates in the intense heat near the surface, ruling out any possibility of rain. This often gives rise to desert climate. That is what has led to the formation of tropical deserts such as the Sahara of Africa and the Sonoran of Mexico.

During winter, winds can make a lot of difference in the way we feel the cold. How cold we feel often depends on the wind velocity. A day with a strong wind can seem much colder than one with only a mild wind, though the air temperature may be exactly the same. The effect that wind has on our perception of cold is called the 'wind chill factor'. The greater

the wind speed, the faster we lose body heat. As a result, wind chill can make a fairly moderate winter day feel like a much colder one. For example, a day with a temperature of 4°C might seem of little concern, but combined with winds of 20 kilometres per hour, it can feel like -5°C ; if the wind speed is 60 km/h then it would feel like -12°C . Wind chill is often the main cause of frostbite suffered by mountaineers.



During winter, winds can make a lot of difference in the way we feel the cold. The 'wind chill factor' tells us how cold we feel at different velocities of wind, the air temperature remaining the same. The figures in blue shaded areas show the perceived temperatures at different wind speeds.

Jet streams

We have been talking about winds that mostly remain confined to the troposphere, where most weather phenomena occur. But there is also a different kind of wind – currents of

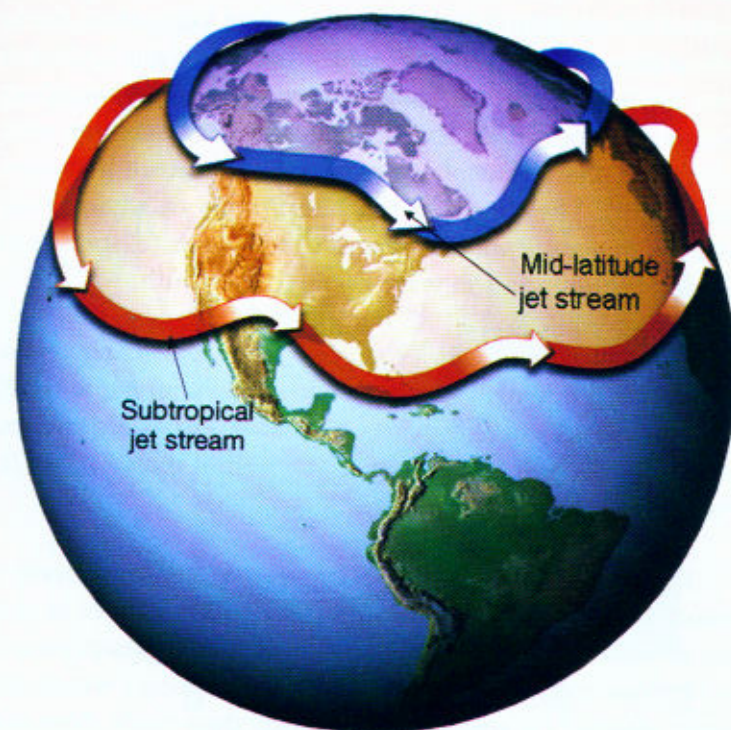
fast moving air blowing in narrow streams, known as 'jet streams' – found in the upper levels of the atmosphere. These rapid currents, which blow in a generally west-to-east direction, are typically thousands of kilometres long, a few hundred kilometres wide, and only a few kilometres thick. Jet streams are usually found somewhere between 10-15 km above the Earth's surface, in the tropopause, at the boundary between the troposphere (where temperature decreases with height) and the stratosphere (where temperature increases with height). They form at the boundaries of adjacent air masses with significant differences in temperature, such as of the polar region and the warmer air to the south.

The wind speeds in jet streams vary according to the temperature gradient, averaging 55 km/h in summer and 120 km/h in winter, although speeds of over 400 km/h are known. Technically, the wind speed has to be higher than 111 km/h to be called a jet stream.

During the winter months jet streams become stronger because the surface temperature contrasts are greater at this time of year. The greater the contrast in surface temperature, the stronger the jet streams blow. Since jet stream winds are greatly affected by surface temperature, their route does not always flow in a uniform west-to-east direction. Often they might head due north and then arc down in a southerly direction, creating a wavy pattern. Jet streams not only steer storms, but also help determine the locations of areas of high and low air pressure at the Earth's surface.

Two different kinds of jet streams are sometimes distinguished. The predominant one, the polar-front jet stream, is associated with the polar front of middle and upper-middle latitudes. The other is the subtropical jet stream is found, at some longitudes, between 20° and 30° latitude and

is strongest off the Asian coast. Jet streams also play an important part in the creation of super-cells, the storm systems which create tornadoes.

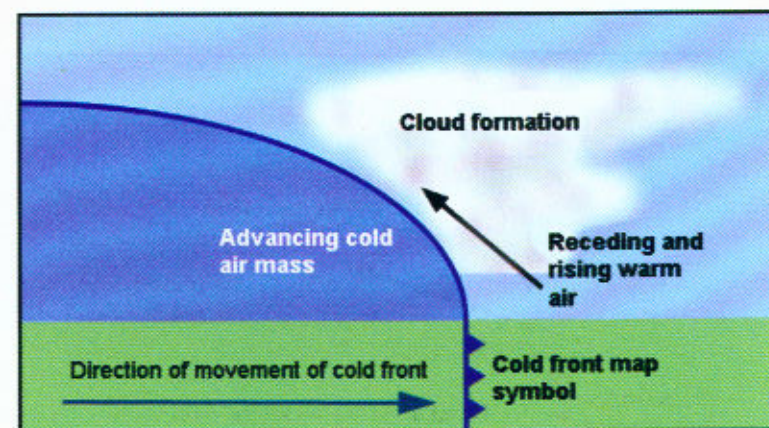


Jet streams are currents of fast moving air blowing in narrow streams in the upper levels of the atmosphere.

The location of the jet stream is extremely important for airlines. In the United States and Canada, for example, the time needed to fly east across the continent can be reduced considerably if an aircraft flies with the jet stream. If it flies west against the jet stream, the flying time increases by a similar amount. That is why, on longer intercontinental flights, pilots usually prefer to fly along the jet stream while flying east and avoid the jet stream when flying west.

Weather fronts

We know that warm air is lighter than cold air. So what would happen when two air masses of different temperatures and densities meet? Obviously they cannot mix together immediately owing to their different densities. Instead the lighter, warmer air mass begins to rise above the cooler, denser one. The transition zone that lies between them is known as weather front.

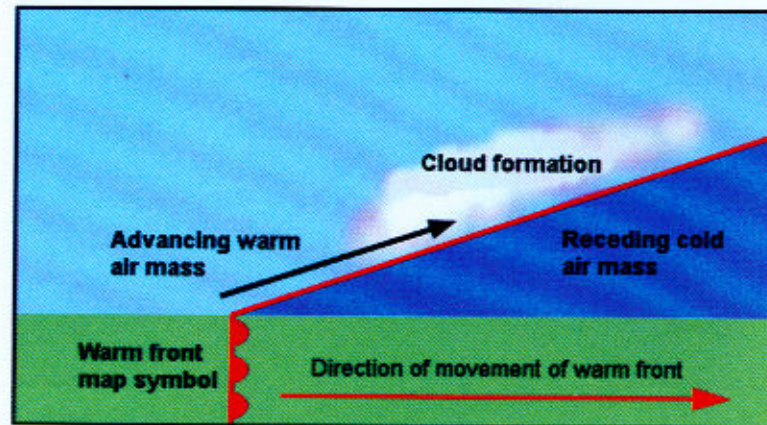


A cold front occurs when a colder air mass meets a warmer air mass.

Weather fronts are always accompanied by clouds of all types, and very often by precipitation. But, when a weather front passes over an area, it is marked also by changes in wind speed and direction, atmospheric pressure, and moisture content of the air. Meteorologists recognise four types of fronts: cold front, warm front, occluded front, and stationary front. The type of front depends on both the direction in which the air mass is moving and the characteristics of the air mass.

Cold fronts occur when a colder air mass replaces a warmer air mass. At cold front the cold air follows the warm

air, and, because cold air is denser, pushes warm air out of its way, forcing the warm air to rise. The lifting warm air mass becomes cooler, and clouds start to form. Precipitation at cold fronts is usually heavier although less extensive (50-70 km) and less prolonged. Towering clouds form, and rain, thunderstorm, hail, and tornadoes can occur in this way. The air behind a cold front is noticeably colder and drier than the air ahead of it. When the cold front passes through, temperatures can drop more than 15 degrees within the first hour.



When a warmer air mass approaches a colder air mass a warm front is created.

Warm fronts occur when a warmer air mass approaches a colder air mass. The warmer air lifts up and over the colder air. Warm fronts are usually gentler than cold fronts, move slowly, gently settling over the cold front and moving it out of the way. Precipitation at warm fronts are usually less heavy although more extensive (300-400 km), than at the cold fronts. The air behind a warm front is warmer and moister than the air ahead of it. When a warm front passes through, the air becomes noticeably warmer and more humid than it was before.

The Beaufort scale of wind force

| Beaufort Number | Wind speed (km/h) | Description | Sea conditions | Land conditions |
|-----------------|-------------------|-----------------|---|--|
| 0 | 0 | Calm | Flat | Calm. Smoke rises vertically. |
| 1 | 1-6 | Light air | Ripples without crests. | Wind motion visible in smoke. |
| 2 | 7-11 | Light breeze | Small wavelets. Crests of glassy appearance. | Wind felt on exposed skin. Leaves rustle not breaking. |
| 3 | 12-19 | Gentle breeze | Large wavelets. Crests begin to break; scattered whitecaps. | Leaves and smaller twigs in constant motion. |
| 4 | 20-29 | Moderate breeze | Small waves. | Dust and loose paper raised. Small branches begin to move. |
| 5 | 30-39 | Fresh breeze | Moderate (1.2 m) waves. Some foam and spray. | Smaller trees sway. |
| 6 | 40-50 | Strong breeze | Large waves with foam crests and some spray. | Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. |

| | | | | |
|----|---------------|---------------|--|--|
| 7 | 51-62 | Near gale | Sea heaps up and foam begins to streak. | Whole trees in motion. Effort needed to walk against the wind. |
| 8 | 63-75 | Gale | Moderately high waves with breaking crests forming spindrift. Streaks of foam. | Twigs broken from trees. Cars veer on road. |
| 9 | 76-87 | Severe gale | High waves (6-7 m) with dense foam. Wave crests start to roll over. Considerable spray. | Light structural damage. |
| 10 | 88-102 | Storm | Very high waves. The sea surface is white and there is considerable tumbling. Visibility is reduced. | Trees uprooted. Considerable structural damage. |
| 11 | 103-119 | Violent storm | Exceptionally high waves. | Widespread structural damage. |
| 12 | 120 and above | Hurricane | Huge waves. Air filled with foam and spray. Sea completely white with driving spray. Visibility greatly reduced. | Considerable and widespread damage to structures. |

When a cold front overtakes a warm front an occluded front is formed. Changes in temperature, dew point temperature, and wind direction can occur with the passage of an occluded front. When a warm or cold front stops moving, it becomes a stationary front. A noticeable temperature change and/or shift in wind direction is commonly observed when crossing from one side of a stationary front to the other.

The Beaufort scale

As we have already seen, the wind velocity can vary over a wide range, depending on the location and season. It may be just perceptible or may be strong enough to uproot trees and topple light buildings. The Beaufort scale is an empirical measure for describing wind velocity based mainly on observed sea conditions. Its full name is the 'Beaufort wind force scale'. The scale was created in 1805 by Irishman Sir Francis Beaufort, a British admiral and hydrographer as a means for sailors to gauge wind speeds through visual observations of the state of the sea. Land based equivalent observations were added later on. The scale runs from force 0 (calm) to force 12 (hurricane)

Winds of the World

In many countries there are local names for specific winds that have some special characteristics. Here are some of them.

Berg

A hot dry wind in South Africa that blows from the interior.

Brickfielder

A very hot north-east wind, which blows during the summer months in south-east Australia, and carries dust and sand.

Buran

A strong north-easterly wind that blows across eastern Asia, specifically Xinjiang, Siberia, and Kazakhstan and takes two forms. In summer, it is a hot, dry, wind, whipping up sandstorms; in winter, it is bitterly cold and often accompanied by blizzards.

Chinook

A wind that blows to the east of the Rockies in the United States, which is warm and dry, and often spells the end of the winter's snow. It takes its name from a local American Indian tribe and means 'snow eater'.

Föhn

A dry, warm wind that blows in the European Alps, but is now used as a generic term for any similar lee wind. It gains its warmth from the air being compressed as it descends down the lee slope of a mountain and historically has been blamed for symptoms such as headaches, depression and even suicide among people living in its path.

Khamsin

A hot, dry southerly wind that blows from the interior of Africa over Egypt and into the eastern Mediterranean. It is a dust laden wind which devastates crops and is feared by the locals. It is common in late spring and early summer.

Loo

A dry, blistering westerly desert wind that blows in from the Rajasthan desert in India during summer. It is said the hotter the loo the sweeter would be the watermelons that are grown on the river bed of the Yamuna in Delhi.

Marin

As the Sirocco (see below) moves across the sea it picks up a lot of moisture. It can blow into the south coast of France as a strong warm and wet wind called the Marin.

Mistral

The Mistral usually develops as a cold front moving down across France, piling up the air in the Alps, before spilling over the top and rushing down the Rhône valley between the Alps and Cevenes mountains. It can reach speeds of up to 150 kmph towards the French Riviera and the Gulf of Lyon. It usually brings dry, but colder and sunnier weather and is likely to cause heavy seas, making it a surfer's paradise.

Nor'wester

A squally wind of northern and eastern India and Bangladesh that blows from the northwest and often brings dust storms and cooling thundershowers in late spring or early summer.

Pampero

A very cold south westerly wind from the Andes that sweeps across the pampas of Argentina and Uruguay and is often accompanied by storms and a severe drop in temperature.

Seistan

A very strong summer wind from the north in eastern Iran, known as the 'wind of 120 days' as it lasts about four months. It can reach hurricane force and carries dust.

Shamal

A north-westerly summer wind that blows over Iraq and the Persian Gulf. It normally decreases at night, and is hot and dry. It is known to whip up the sand and reduce the visibility to a few hundred metres.

Sirocco (or Scirocco)

A strong southerly wind – often very hot and dry – that develops ahead of a depression moving into the central Mediterranean near North Africa. If the conditions are right these winds move across the Mediterranean, pick up moisture from the sea and by the time they reach Europe they bring warm, humid air and low cloud.

Vendavales

Strong south-westerly winds that blow in the straits of Gibraltar in late autumn through the winter, as Atlantic depressions enter the western side of the Mediterranean. This wind is known as the Vendavales and is associated with very squally weather with thunderstorms.



Clouds, Rain and Snow

If we were to travel 35 kilometres or so above the Earth's surface during the day, the sky would appear black. We may be even able to see the stars! In fact, when astronauts fly in space they do not see a blue sky when they look out of their spacecraft because there is no atmosphere in space.

As we have seen earlier, on a sunny day the cloudless sky from ground looks blue because the dust and gas particles in the atmosphere scatter blue colour of the sunlight more than the other colours. As a result we see the scattered blue light coming from all directions of the sky. This is what makes the daytime sky appear blue from ground.

But the daytime sky does not always remain blue. At times it is covered by clouds, which are masses of tiny floating droplets of water that come in varied shapes and often cause rain. Many of us have had the experience of a weekend picnic marred by the sudden appearance of dark clouds and rain. But not all clouds bring rain and if we spend some time watching the clouds we will find it a fascinating experience. They present an ever-changing pattern of myriad shapes on the broad canvas of the sky.

Clouds are a major part of our weather. When the Sun heats up the surface of the Earth it causes water from rivers, lakes or oceans to go into the air and turn into water vapour by a process called evaporation. Clouds are formed from warm air that rises up carrying water vapour in it. The water vapour cools as the warm air rises higher. When it cools it changes into tiny droplets of water or crystals of ice. This occurs because cool air can hold less water vapour than warm air, and the excess water condenses into either liquid or ice, depending on the surrounding temperature. Clouds form when these droplets of water collect around small bits of dust, sea salt or pollution floating in the air.



The evaporation of water from oceans and land, condensation of the vapour into cloud and precipitation from the cloud as rain and snow constitute the Earth's water cycle.

The droplets bump into each other and get bigger and bigger. When the water droplets become too heavy to stay in the air they fall to the ground as rain or snow. Another word for rain or snow is 'precipitation'. Some of this precipitation collects into the rivers, lakes and oceans on Earth and starts the cycle all over again.

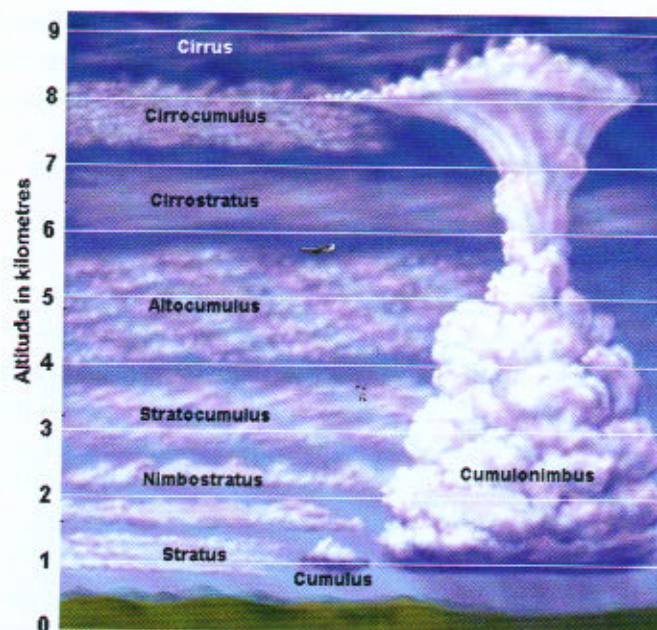
The most interesting thing about clouds is the large variety of shapes that they come in. They range from light, featherlike clouds that appear scattered across the sky to the huge thunderheads that sometimes appear to cover the entire sky. There are clouds that float across the blue autumn sky with gay abandon, like puffs of white cotton, while others appear more intimidating and bring thunder, heavy rain and deluge in their wake.

Cloud names

Like us humans, clouds, too, are known by different names. From the ground all clouds appear to be at the same height and most of us would not find much difference between them, but it is not so. Those of us who have travelled by air know that from that height we can see clouds below us and also clouds much above us. We have also noticed the variety of shapes and forms that clouds appear in. Although in the mountains clouds start forming almost at the ground level, the altitude at which clouds usually appear ranges between 1,800 m and 5,500 m. But some clouds that cause thunder and rain may rise up to heights of 15,000 m and above.

Meteorologists identify clouds by different names, depending on their shape and the height at which they appear. There are three main families of clouds: cirrus, cumulus, and stratus. These are the Latin names given to clouds in 1804. *Stratus* means 'layer', *cumulus* means 'heap', and *cirrus* means 'curl of hair'.

Clouds can also be classified by their altitude, whether they are located low, middle or high in the sky. For example, *cirro* (meaning 'wisp of hair') is a prefix given to high-altitude clouds (above 6,000 m). Clouds that occur at altitudes between 1,800 and 6,000 m have *alto* (meaning 'high') added to their name. There is no prefix for low-altitude clouds. When clouds form near the ground we call them fog. Clouds with *nimbus* in their name are rain-bearing clouds.



Different types of cloud appear at different altitudes.

Some of the main cloud forms that we usually come across at different times are the following:

- Stratus clouds are uniform, thin-layered clouds that are seen below 1,800 m. They look like a low gray blanket. Fog is a stratus cloud at ground level. Stratus clouds can bring rain or snow.



Stratus clouds

- Cumulus clouds are puffy clouds that appear below 1,800 m. Cumulus clouds have flat bottoms and appear low in the sky. They usually mean fair weather, but if they grow tall, they can become thunderheads and bring rain.



Cumulus clouds

- Stratocumulus clouds are broad and flat on the bottom and puffy on top and occur below 2,000 m. These clouds vary in colour from dark gray to light gray and may appear as rounded masses, with breaks of clear sky in between. They sometime cause light rain.

*Stratocumulus clouds*

- Altocumulus clouds are medium-sized puffy clouds that appear between 1,800 m and 6,000 m. They look like dozens, of small, loose cotton balls. Altocumulus clouds usually form in groups and are about 1 km thick.
- Cirrocumulus clouds are small puffy clouds seen above 5,500 m. Like all

*Altocumulus clouds*

high-level clouds, cirrocumulus is made of ice crystals. Cirrocumulus clouds rarely cover the entire sky and are sometimes hard to detect.

*Cirrocumulus clouds*

- Cirrus clouds are thin and wispy clouds seen above 5,500 m. They are composed of ice crystals that originate from the freezing of supercooled water droplets. Cirrus clouds generally occur in fair weather and point in the direction of air movement at their elevation.

*Cirrus clouds*

- Cumulonimbus clouds are huge column-shaped clouds that may reach heights of more than 15,000 m; that is, 15 km. They are capable of producing heavy rain, high



Cumulonimbus clouds

winds, and lightning. Cumulonimbus clouds can produce rain showers, snow showers, hail, or even thunderstorms.

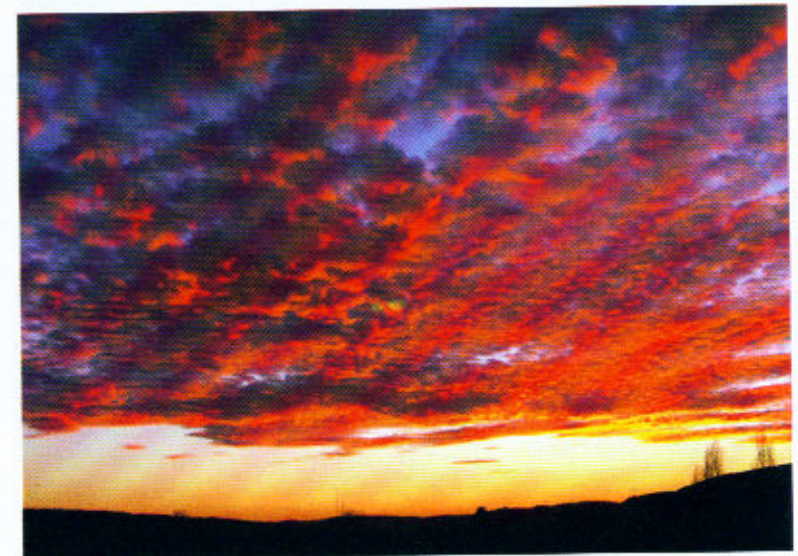
Colours of clouds

Clouds mostly appear white against the blue of the sky because the water droplets that make up clouds are much larger than the molecules that scatter blue light. The clouds scatter and reflect all the visible colours of light that strike them, making them appear white.

As a cloud grows, the droplets may combine to produce larger droplets, which may themselves combine to form droplets large enough to fall as rain. In this process, the space between droplets becomes larger and larger and sunlight can penetrate much farther into the cloud. If the cloud is sufficiently large very little light that enters the cloud is reflected back before it is absorbed and the cloud appears

light or dark gray in colour. When we see such dark clouds we may be sure of rainstorm or snow.

We often see clouds of red, orange and pink colours. Normally such colours are seen only at the times of sunrise or sunset. But the clouds themselves are not coloured; they get their colours from sunlight scattered by dust and gas



Clouds often look colourful during sunrise and sunset due to sunlight scattered by dust and gas particles in the atmosphere.

particles in the atmosphere. The effect is much the same as happens when we shine a red spotlight on a white sheet; the sheet appears red in colour. During the rainy season we often see huge thunderheads with red tops just before or soon after sunset. The interesting thing is that unlike the white or gray clouds the colour of which remains unchanged for a long time, the colour of red, orange, or pink coloured clouds change rapidly, as the Sun sinks below the horizon, and watching the colours change is a unique experience.

Cloud watching can be an enjoyable pastime. By learning to identify the different types of clouds it is possible to tell what the weather would be like in the next few hours or days, for example. Even if we cannot do that, just watching



A huge thunderhead coloured red by setting Sun.

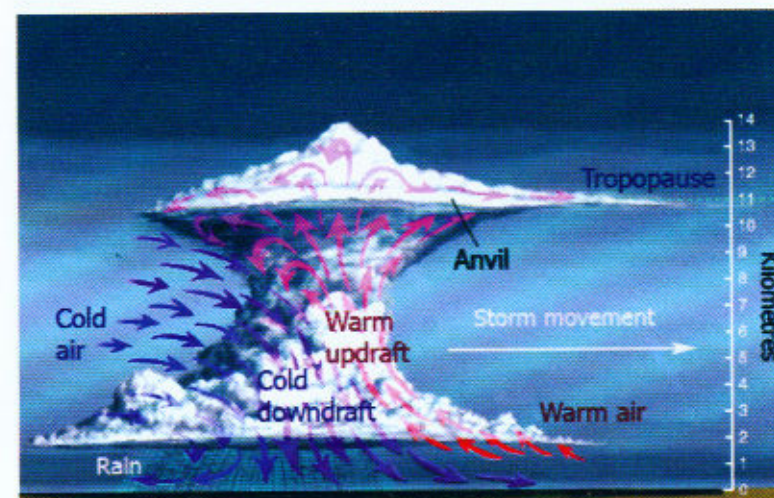
the movement of the clouds in the sky can provide hours of joy.

Clouds are so fascinating that they even have a 'Cloud Appreciation Society' in England whose motto is: "Look up, marvel at the ephemeral beauty, and live life with your head in the clouds!"

Lightning and thunder

Cumulonimbus clouds are much larger and more vertically developed than cumulus clouds which form in a more stable

atmosphere. Fuelled by vigorous convective updrafts, the tops of cumulonimbus clouds can easily reach 15,000 metres. Lower levels of cumulonimbus clouds mostly consist of water droplets while at higher elevations, where temperatures are well below 0°C, ice crystals dominate. Cumulonimbus clouds typically produce lightning and thunder and are generally



Profile of a thunderhead.

referred to as thunderclouds or thunderheads. Lightning is an abrupt, high-current electric discharge that occurs between clouds or between cloud and the Earth's surface and is often associated with thunder, which is the crashing or booming sound produced by rapidly expanding air along the path of the electrical discharge of lightning.

A typical lightning bolt has a path length ranging from hundreds of metres to tens of kilometres. It was long believed that lightning occurs in thunderstorms because vertical air motions and interactions between water droplets in the cloud cause a separation of positive and negative charges. Now scientists have found experimental



A powerful bolt of lightning striking ground.

proof of exactly how clouds get charged – and the cause is tiny ice crystals. It may seem hard to believe that a powerful bolt of lightning, which heats the air in its path three times hotter than the surface of the Sun, could spring from little

pieces of ice. But that is how it is, as has been confirmed by laboratory experiments.

Fog, rain and snow

As we have seen, clouds form when moist air rises, expands and cools, and the water vapour condenses into fine droplets.



Fog at airports severely hampers traffic during winter.

Sometimes, the water vapour in air can condense into droplets even without rising, if conditions are favourable. We then call it 'fog'.

Fog is quite common in hill stations where it is not much different from cloud formed at ground level, although at a higher altitude. As moist air rises along the hill slope it cools and condenses. In the plains fog occurs mostly in winters

when the temperature falls below the 'dew point' – the temperature at which air becomes saturated when cooled without addition of moisture or change of pressure; any further cooling causes condensation.

Meteorologists classify fogs into four different types: radiation fog, advection fog, hill fog, and coastal fog, all of which can be a hazard for road users, airline pilots, and even ship captains, as the *Titanic* disaster of 1912 so tragically demonstrated.

Radiation fog is formed on clear, still nights when the ground loses heat by radiation, and cools. The ground in turn cools the nearby air to saturation point, thus forming fog. Often the fog remains patchy and is confined to low ground, but sometimes it becomes more dense and widespread through the night. After dawn, fog tends to disperse because of heating by the incoming solar radiation, some of which penetrates the fog and reaches the ground. The ground heats up, as does the layer of air near it. Eventually, the air reaches a temperature where the minute fog droplets evaporate and the visibility improves.

Advection fog is formed when very mild moist air moves over a cold ground. This can often happen in early spring in the northern latitudes when mild south-westerly winds move across over snowy or icy ground. The lower layers of the air get cooled down rapidly to below the temperature at which fog forms.

Hill fog, as its name implies, is formed as mild moist air is forced to ascend a hill or mountain range. As the air moves up the windward side of the mountain it cools down. In the process if the air becomes saturated then cloud is formed which, if below the top of the hills, gives fog.

Coastal fog mostly occurs in coastal regions, especially in the northern latitudes when moist air is cooled to saturation point by travelling over a cooler sea. The wind may then take the fog into coastal regions. This type of fog tends to occur in spring and summer, and particularly affects south western and North Sea coasts of the British Isles.

Fog and mist are both made of tiny water droplets suspended in air. The difference between them is the density of the droplets. Fog is denser so contains more water droplets than mist. The official definition of fog is a visibility of less than 1,000 metres. This limit is appropriate for aviation purposes, but for general public and motorists an upper limit of 200 metres is more realistic. Severe disruption to transport occurs when the visibility falls below 50 metres.

Rain and snow

Precipitation forms when cloud droplets (or ice particles) in clouds grow and combine to become so large that the updrafts



During a heavy shower raindrops can be up to 64 mm in diameter.

in the clouds can no longer support them, and they fall to the ground. The more water vapour there is below the cloud, and the stronger the updrafts that cause this water vapour to condense into cloud water or ice particles, the more likely it is that precipitation will form within the cloud.

The chief difference between a cloud drop and a rain drop is size. A typical rain drop has a volume that is more than a million times that of a cloud drop. Thus it takes many



After heavy snowfall the landscape appears covered with a white blanket.

cloud droplets to make up a single raindrop. Although raindrops form by the collision and merging of numerous cloud droplets, they are much smaller than we think! They are actually smaller than a centimetre. Raindrops range from 0.0254 cm to 0.635 cm in diameter. In still air, raindrops fall between 3 and 8 metres per second. The range in speed depends on the size of the raindrop.

Raindrops are also produced by the melting of ice crystals, snowflakes, and other frozen particles. When ice crystals exist in the presence of 'supercooled' water droplets in air below the freezing point, the crystals grow as the droplets evaporate. There is a pressure force driving the water molecules from the water to the ice, resulting in a rapid growth of ice crystals in the presence of liquid cloud droplets. If the temperature is below freezing snow flakes form and float down silently covering the landscape with a white blanket.

As ice crystals grow, the heavier ones fall. As a result, collisions and merging occur. A snowflake can be made up of a group of crystals stuck together. When such a particle falls through a layer of air whose temperature is above freezing, the crystals melt and raindrops are produced. In mountainous areas during the winter, the valleys below often experience rain while snow falls at higher elevations.

We must remember here that all of the precipitation that falls as rain or snow anywhere in the world originated as water vapour that was produced by evaporation from the surface of the Earth. It is always raining somewhere on the Earth, just as evaporation is always occurring over most of the Earth's surface. At any given time, precipitation covers only about 2% to 5% of the surface of the Earth, while evaporation is occurring over the remaining 95% to 98% of the Earth. We can say that water vapour gets 'concentrated' into relatively small rain systems around the globe that turn this vapour into precipitation.

Measuring rain and snow

We are familiar with terms like '200 mm of rainfall', but what do they mean. What does '200 mm' mean here? Actually it is

the height up to which the accumulated water would rise if all the rain fell on a perfectly flat surface, and indirectly gives a measure of the volume of water falling as rain. Thus, if it rained 200 mm over an area of 10 km², then the total volume rain water would be $[(10 \times 1000 \times 100 \times 10)^2 \times 200] \text{ mm}^3$. Converted into litres it comes to 2×10^{10} litres, or 2,00,00,000 m³. A rain gauge is really just a device that catches rain falling over a certain area, the volume of which can be measured with a measuring cylinder and the quantum of rainfall computed in mm.



Rain gauge is used to measure rainfall.

Rain gauges are thought to be the most ancient weather instruments. They are believed to have been used in India more than 2,000 years ago. In Kautilya's *Arthashastra*, for

example, mention is made of the use of rain gauges to set precise standards of grain production. Each of the state storehouses was equipped with a standardised rain gauge to classify land for taxation purposes.

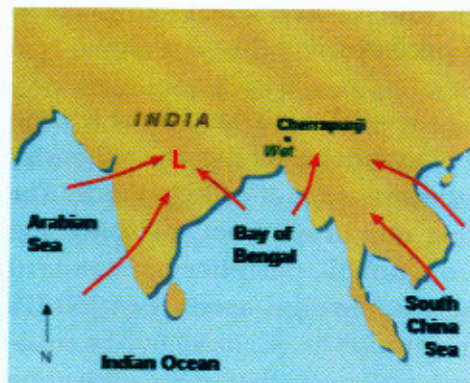
Most standard rain gauges have a wide funnel leading into a measuring cylinder of such diameter that one millimetre of rain measures one centimetre when it collects inside. The funnel prevents the falling rain drops from splashing and spreading outside the funnel periphery. Standard meteorological gauges have a funnelled aperture of 150-170 cm, and are set 30 cm above ground level. Normally, the cross-sectional area of the funnel is 10 times that of the measuring cylinder. Rainfall as low as 0.02 mm can be measured with this instrument. Anything under 0.02 mm is considered a 'trace'.

Snowfall is measured in a similar way. Snow is collected on a platform, melted and the volume of water formed is measured. The recorded precipitation is always expressed in terms of rainfall or melted snow. On the average, 10 mm of snow is equivalent to one mm of rain, but that is only an average. Snowfall is also expressed in the terms of the actual depth of the falling snow. That depth is determined by taking an average of three or more representative spots. A ruler is stuck into the snow, and its depth is recorded. Because of blowing and drifting, the determination of three or more representative locations is not always easy.

The monsoons

The Indian subcontinent receives more than 80% of the annual rainfall during the four-month period during the summer monsoon. Monsoon is a term from early Arabs called the *Mausin*, or 'the season of winds.' This was in reference to the

seasonally shifting winds in the Indian Ocean and surrounding regions, including the Arabian Sea. These winds blow from the southwest during one half of the year and from the northeast during the other.



During the summer monsoon, moisture-laden winds blow onto the Indian subcontinent from the southwest.

from June to September. The torrential rainstorms often cause violent landslides and widespread floods. Entire villages have

The summer monsoon – also known as the ‘southwest monsoon’ – blows onto the subcontinent from the southwest. The winds carry moisture from the Indian Ocean and bring heavy rains



Monsoon rains regularly cause devastating floods in many parts of Southeast Asia.

been swept away during monsoon rains. Despite the potential for destruction, the summer monsoons are welcomed in India. Farmers depend on the rains to irrigate their land. Additionally, a great deal of India’s electricity is generated by water power provided by the monsoon rains.

The period October to December is referred to as the ‘northeast monsoon’ season over peninsular India. During this period the monsoon winds blow from the northeast and bring copious rain in the coastal areas along the Bay of Bengal.

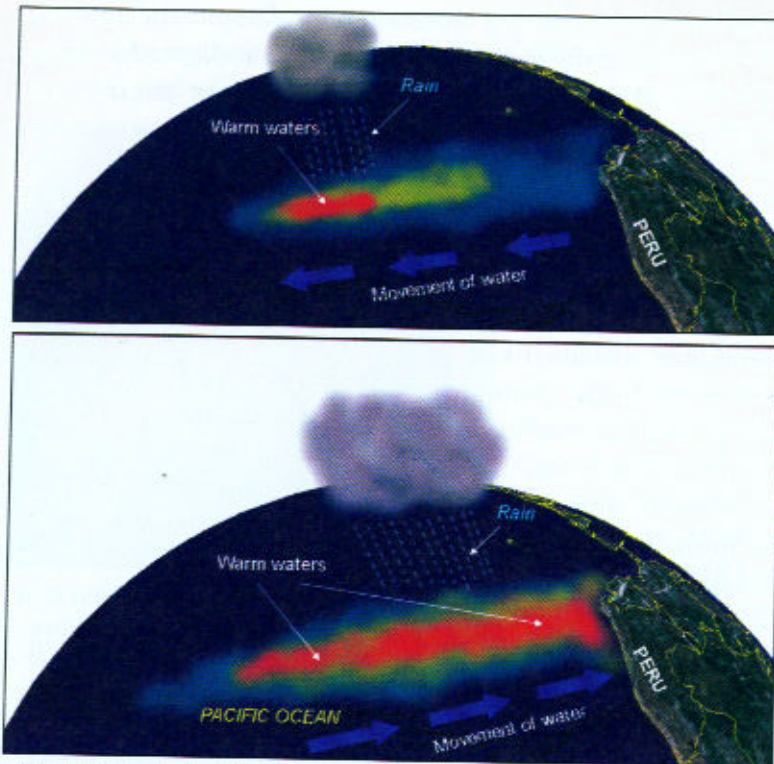


During the winter, monsoon winds blow from the northeast and bring copious rain in the coastal areas of peninsular India along the Bay of Bengal.

El Niño

There are several factors that influence the Indian monsoon. Among them is El Niño, a temporary change in the climate of the Pacific Ocean, in the region around the equator off the coast of Peru. Usually, the wind blows strongly from east to west along the equator in the Pacific. As a result, in the eastern part, deeper water (which is colder than the Sun-warmed surface water) gets pulled up from below to replace the water pushed west. So, the normal situation is warm water (about 30°C) in the west and cold water (about 22°C) in the east.

In an El Niño, the winds pushing the water around get weaker. As a result, some of the warm water piled up in the west slumps back down to the east, and not as much cold water gets pulled up from below. Both these tend to make the water in the eastern Pacific warmer, which is one of the hallmarks of an El Niño. The occurrence of an El Niño depends



Under normal situation the water is warmer in the west and cold in the east in the Pacific off the coast of Peru (top). During an El Niño, water in eastern parts of Pacific off the Peru coast tends to become warmer, which disrupts the normal weather pattern elsewhere, including the Indian monsoon (bottom).

on whether the surface of the equatorial Pacific Ocean is warmest in the east, along Latin America, or closer to the centre.

The effects of an El Niño can be seen in both the ocean and atmosphere, generally in Northern Hemisphere winter. Typically, the ocean surface warms up by a few degrees Celsius. At the same time, the place where hefty thunderstorms occur on the equator moves eastward.

Although these anomalies might seem like small differences, they can have big effects on the weather in distant places.

For example, the 132-year historical rainfall record of India reveals that severe droughts in India have always been accompanied by El Niño events. Yet not all El Niño events have produced severe droughts. It was a mystery that researchers have been struggling to crack. Accurate monsoon prediction is crucial to India's economy because nearly one-fifth of the country's gross domestic product comes from agriculture. Even moderate crop failures have severe economic and societal impacts. So it was essential to know just how El Niño influenced the Indian monsoon. The mystery now appears to have been cracked; it has been found that El Niño events with the warmest sea surface temperature anomalies in the *central* equatorial Pacific Ocean are more effective in producing drought-producing conditions over India than events with the warmest sea surface temperatures in the *eastern* equatorial Pacific Ocean.

Droughts

If excessive rainfall causes floods, drought is the other extreme – almost total lack of rainfall. Most parts of the world, except the desert regions, receive regular rainfall throughout the year. In countries like India the annual monsoons bring copious rainfall to sustain agriculture and water needs. But occasionally the rains fail, leading to conditions of drought. When there is drought there is acute scarcity of water and extensive loss of crop. In India it is not uncommon to have floods in one part of the country and drought in another part at the same time. What causes drought?

Drought in simple terms is the dryness due to insufficient rainfall or shortage of water for an extended period – a season,

a year or several years over a particular region. Drought caused by lack of sufficient rain is defined as meteorological drought, which happens when the actual rainfall in an area is significantly less than the average rainfall of that area. The country as a whole may have a normal monsoon, but different meteorological districts and sub-divisions can have below normal rainfall.



Failure of rain over a long period often leads to drought when there is acute scarcity of water and extensive loss of crops and livestock.

A drought occurs when not enough rain falls to the ground, and rainfall can occur only if water vapour condenses, which happens only if air rises into the colder regions of the atmosphere. If the air does not rise, then no rain will form. When there is high air pressure, air does not rise and no currents of water vapour are carried upward. As a result, no condensation occurs, and little rain falls. In addition, high-pressure areas also push clouds and air currents away, resulting in sunny, cloudless weather. Low-

pressure systems on the other hand see more cloudy and stormy weather.

Usually we experience both high- and low-pressure systems. It is normal for a high-pressure system to pass over an area and move on, being replaced by a low-pressure system bringing rain. However, when a high-pressure system is stalled, the sunny weather can drag on for days resulting in a drought. Jet streams in the upper atmosphere can stall high-pressure systems and thus prevent rainfall.

Droughts also occur because water vapour is not brought by air currents to the right areas at the right times. Water that evaporates from the oceans is brought inland by wind to regions where it is needed. However, sometimes those winds are not strong enough. In south-east Asia, usually, the summer monsoons carry water vapour north from the Indian Ocean inland, providing desperately needed rain. Sometimes, due to events like El Niño in central equatorial Pacific Ocean, the monsoon circulation is disrupted and not enough moisture reaches the Indian subcontinent, leading to monsoon failure and drought.



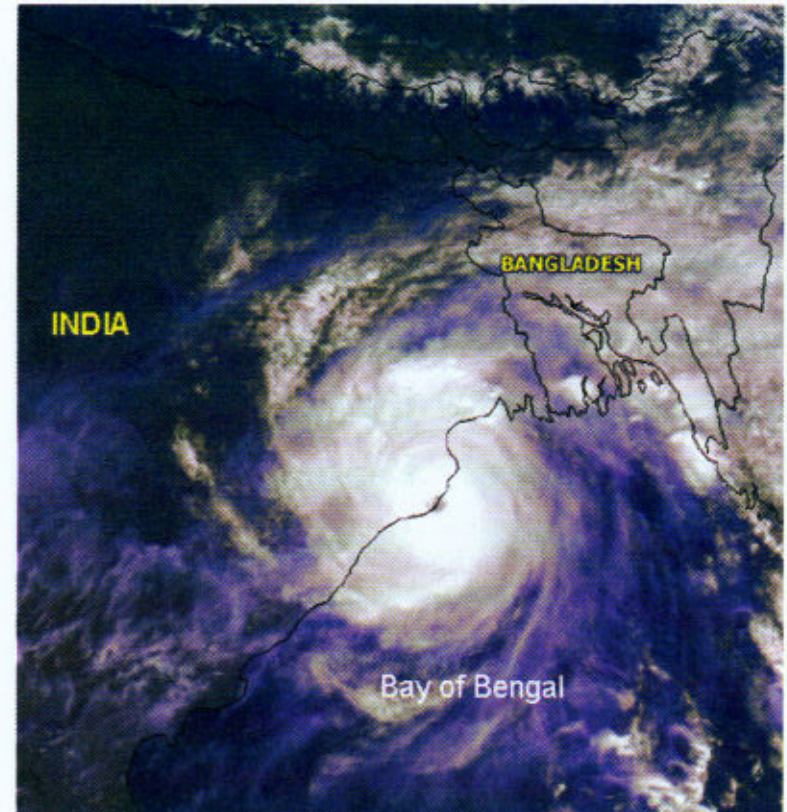
Violent Weather

Rain, snow, and thunderstorms are common experiences for most of us. We do not panic if the rain continues for a few days or a severe thunderstorm lasts for a few hours. But occasionally things go really bad. When a severe cyclonic storm hits the coast it can bring torrential rain and deluge inundating large areas and causing extensive loss of life and property. In the central plains of the United States and even in some parts of India violent whirlwinds known as tornadoes often strike, wreaking havoc in a matter of just a few minutes. These weather phenomena are among the most violent seen in nature and cause extensive damage worldwide. But they are also Nature's ways of maintaining the heat balance of our planet – cyclones and hurricanes maintain equilibrium in the Earth's troposphere and help maintain a relatively stable and warm temperature worldwide.

Cyclones, Hurricanes, Typhoons

We are all familiar with the terms cyclones and hurricanes, which cause extensive damage to property and often take heavy tolls of human life around the world. For example, the severe cyclone that hit the coast of Bangladesh in 1991 killed

more than 139,000 people. The super cyclone that crossed the Orissa coast in October 1999 killed as estimated 10,000 people. Hurricane *Katrina* that hit New Orleans in USA in 2004 caused extensive damage to the town's infrastructure and left almost 1,500 people dead.

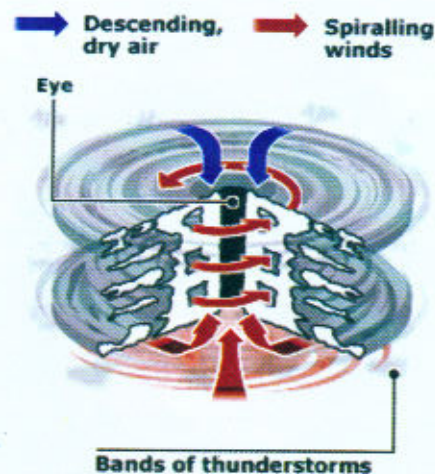


Satellite picture of the super cyclone that hit the coast of Orissa in October 1999.

Cyclone is, in fact, one of the three names for rotating tropical storms with winds of at least 110 km/h. These storms are called 'cyclones' when they form over the Bay of Bengal and northern Indian Ocean. They are called 'hurricanes' when

they develop over the Atlantic or eastern Pacific Oceans, and they are known as 'typhoons' when they develop in the western Pacific Ocean.

A tropical cyclone is a meteorological term for a storm system characterised by a low pressure system at centre and thunderstorms that produces strong wind and torrential rain. Cyclones develop over warm seas near the equator. When warm air rises from the seas and condenses into clouds, massive amounts of heat are released. The result of this



Inside a tropical cyclone.

mixture of heat and moisture is often a collection of thunderstorms, from which a tropical storm can develop. As warm air rises, cool air rushes in to fill the void that is left, but because of the constant turning of the Earth on its axis, the air is bent inwards and then spirals upwards with great force. The swirling winds rotate faster and faster, forming a huge circle which can be up to 2,000 km across. At the centre of the storm is a calm, cloudless area called the 'eye', where there is no rain, and the winds are fairly light.

As the cyclone builds up it begins to move, sustained by a steady flow of warm, moist air over the ocean. The strongest winds and heaviest rains are found in the towering clouds which merge into a wall about 20-30 km from the storm's centre. The wind blows in a spiral direction around a relatively calm area known as the eye. The eye is usually 30 to 50 kilometres wide. Winds around the eye can reach speeds



Devastation caused by the super cyclone in Orissa.

of up to 200 km/h. The most violent activity takes place in the area immediately around the eye, called the 'eye wall'.

As the cyclone approaches the coast, the sky begins to darken, and the wind gets stronger. As it nears lands, it may bring torrential rain, storm surges, and very high winds that cause widespread devastation. A tropical cyclone feeds on the heat released when moist air rises and the water vapour it contains condenses.

Tropical cyclones not only produce extremely powerful winds and torrential rain; they are also able to produce high

waves and damaging storm surges. They develop over large bodies of warm water, and lose their strength after moving over land. That is why coastal regions usually bear the brunt of a tropical cyclone, while inland regions are relatively safe from receiving strong winds. Heavy rains, however, can produce significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 kilometres from the coastline.

Cloudbursts

Cyclones and hurricanes are not the only natural phenomena that cause extensive flooding. Occasionally we hear of heavy flooding caused by a cloudburst, as happened in Mumbai in 2005, which caused heavy damage to life and property in the city. In mountainous regions cloudbursts often cause flash floods in small rivers wiping out villages downstream. What is this cloudburst?

According to meteorologists, a cloudburst is a sudden violent rainstorm lasting a short period of time and limited to a small geographical area, typically with a fall rate equal to or greater than 100 mm per hour. In other words, a cloudburst is just an incident of extremely heavy rainfall lasting a few hours.

In the Indian subcontinent, a cloudburst usually occurs when a moisture-laden monsoon cloud drifts northwards, from the Bay of Bengal or Arabian Sea across the plains, then onto the Himalaya and brings rainfall as high as 75 mm per hour. During the cloudburst over Mumbai in July, 2005, more than 950 mm of rainfall was recorded in the city over a span of about ten hours. Cloudbursts frequently occur in Himachal Pradesh during the monsoon.

We do know that most cloudbursts come from convective, cumulonimbus clouds that form thunderstorms

and that the air is generally rather warm in order to contain the amount of moisture needed for a heavy downpour. Cumulonimbus clouds, which reach heights of up to 15 km, also have regions of strong updrafts which hold raindrops aloft en masse and can produce the largest raindrops. These updrafts are filled with turbulent wind pockets that toss small



A cloudburst photographed near Dehra Dun. (Photo: Sandeep Gajjar)

raindrops around with surprising force. If these upward air currents suddenly cease, the entire amount of water coalesces and comes down as intense rainfall on to a small area. It appears as if the cloud has burst open like a soggy paper bag. During a cloudburst, more than 20 mm of rain may fall in a few minutes.

The resulting rainfall is a torrent of water, large raindrops falling at high speed, over a small area. The force and quantity of such downpours can be damaging to vegetation, small animals, and property. When the speed of water accumulation on the ground exceeds the surface's ability to absorb it, localised flooding occurs in low-lying terrain. In hilly or mountainous terrain, the runoff of water can cause flash floods, wiping out villages downstream of the river.

Tornadoes

A tornado is yet another violent weather phenomenon that often strikes suddenly and leaves behind a trail of destruction.



A tornado is a violent rotating column of air extending from a thunderstorm to the ground, which may contain wind speeds of 160 to over 480 kilometres per hour and cause extensive damage to property.

The word tornado comes from the Spanish word *tronada*, or thunderstorm. A tornado is a violent rotating column of air

extending from a thunderstorm to the ground, which may contain wind speeds of 160 to over 480 kilometres per hour. Most tornadoes take on the appearance of a narrow funnel, a few hundred metres across, with a small cloud of debris near the ground. However, tornadoes can appear in many shapes and sizes. The entire tornado moves across the ground at 30 to 65 kilometres per hour, and most last less than 30 minutes, but the destruction it causes may be colossal. The width of a tornado is usually not much larger than the size of a football field, but in some rare cases can be more than a kilometre in width.

Those of us who have seen the 1996 movie *Twister* must have got an idea of how violent tornadoes can be and what devastation they can cause. Indeed, tornadoes are one of nature's most destructive storms; they can destroy large buildings, uproot trees and hurl vehicles hundreds of metres. They can also do strange things; they can lift cattle and drop them safely some distance away, or can even drive straw into trees.

Tornadoes can strike at any time of day, but are much more frequent in the afternoon and evening, after the heat of the day has produced the hot air that powers a 'tornadic thunderstorm' that produces a tornado. A tornadic thunderstorm can form where moist, warm air gets trapped beneath warm, dry air under a stable layer of cold, dry air. In the United States, which witnesses the most intense and devastating tornadoes, they are most common in what has come to be known as the 'Tornado Alley' that lies between the Rocky Mountains to the west and the Gulf of Mexico to the south.

Tornadoes most frequently occur in the United States, which may see as many as 1,400 in a year. But they occur in

other countries also. In India, the states of Orissa and West Bengal are occasionally hit by tornadoes. In 1978, about 150 people were killed by a tornado in Orissa and again in 1998 more than 160 people were killed and more than 2,000 injured when a tornado passed through 20 coastal villages in the West Bengal and Orissa. The tornado flattened 15,000 homes and left more than 10,000 people homeless. In 1978, twenty-eight people were killed and 700 were injured by a tornado that cut a path five kilometres long and 50 metres wide in the northern suburbs of New Delhi, near the University.

Fortunately, advances in weather forecasting techniques have made it possible in many cases to forewarn people about violent weather and move them to safer places. This has reduced loss of life in most cases, but still mankind is defenceless against Nature's violent acts.



Predicting Weather

Weather is so closely related to our daily life that every one of us has a strong desire to know what the weather will be like tomorrow or the next week. After all, who wants a vacation to be spoiled by a sudden spell of rain or bad weather? But it is not always that the forecast made by the local met office turns out to be correct. In fact weather forecasts had long remained a matter of joke for their utter unreliability and even today not many people take it seriously. Why is weather so unpredictable? How are weather forecasts made? Let us see.

A weather forecast is a prediction of what the weather will be like in an hour, tomorrow, or next week. The people who study the weather and make forecasts are called meteorologists. Meteorologists today use ground-based weather data from a large number of locations, satellite images and data, and supercomputers to make their forecasts. But it was not always so.

The beginnings of meteorology

For millennia people have tried to forecast the weather. In 650 BC, the Babylonians predicted the weather from cloud

patterns. In about 340 BC, Aristotle described weather patterns in *Meteorologica*. Chinese weather prediction lore extends at least as far back as 300 BC.

Ancient weather forecasting methods usually relied on observed patterns of events. For example, it might be observed that if the sunset was particularly red, the following day often brought fair weather. This experience accumulated over the generations to produce weather lore. However, not all of these predictions prove reliable and many of them have since been found not to stand up to rigorous statistical testing.

To many of us weather forecasting may appear quite simple. For example, if there are dark clouds on the horizon, the wind is blowing from that direction, and the humidity is very high, we may easily forecast that rains may come in the next few hours. In winter, if the day is cloudy and the sky clears up in the evening, it is quite simple to guess that the night temperature will fall sharply.

But there is more to weather forecasting than little tricks about looking at the clouds and feeling how the wind blows. Modern forecasting involves technology, science and advanced mathematics to accurately predict the weather. Meteorology, as we perceive it now, may be said to have had its firm scientific foundation in the 17th century after the invention of the thermometer and the barometer and the formulation of laws governing the behaviour of atmospheric gases. It was in 1636 that the British astronomer Edmund Halley published his treatise on the Indian summer monsoon, which he attributed to a seasonal reversal of winds due to the differential heating of the Asian land mass and the Indian Ocean. But weather forecasting was still a distant dream.

The modern age of weather forecasting began only after the invention of the telegraph in 1837. Before that, it was not

possible to collect information about the state of the weather simultaneously from a wide area, which is essential for making a forecast. By the late 1840s the telegraph allowed reports of weather conditions from a wide area to be received almost instantaneously. This allowed forecasts to be made by knowing what the weather conditions were like further upwind.

In 1922 the British physicist and psychologist Lewis Fry Richardson proposed the possibility of numerical weather prediction, although at that time computers fast enough to process the vast amount of data required to produce a forecast did not exist. Practical use of numerical weather prediction began in 1955, spurred by the development of programmable electronic computers. Numerical weather prediction uses mathematical models of the atmosphere to predict the weather. Meteorologists use powerful supercomputers to manipulate the huge datasets and perform the complex calculations needed for making a reasonably accurate forecast.

Making a forecast

The first step in weather forecasting is to get information about the weather, or weather data. Data is collected from ground level as well as from different levels of the atmosphere by launching balloons twice a day all around the world. Weather balloons record data such as temperature, pressure, humidity, and wind speed at different heights in the atmosphere.

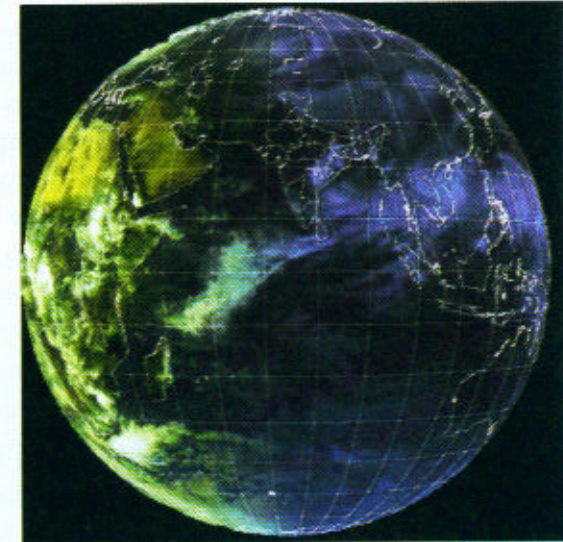
Another useful tool for forecasters is satellite technology. Satellites provide meteorologists almost uninterrupted view of the cloud cover any time of the day. Individual clouds can also be tracked from one time to the next to provide information on wind direction and strength at the clouds steering level. Polar orbiting satellites provide soundings of



Weather data such as temperature, pressure, humidity, and wind speed at different heights in the atmosphere are collected daily by releasing weather balloons carrying radiosondes.

temperature and moisture throughout the depth of the atmosphere. Thus satellites allow meteorologist to monitor cloud formation and their movements round the clock and help them see how the atmosphere is behaving. In particular, satellites make it possible to monitor the formation of cyclonic storms over the sea and predict their likely movement and landfall, which can help in issuing advance disaster warnings.

Meteorologists also make use of what is known as 'Doppler radar' for weather forecasting. Doppler radar is a system for measuring wind speeds based on the Doppler Effect. Doppler radar is now being used by meteorologists to learn even more about weather, especially, dangerous



INSAT-view of the cloud cover over the globe.

weather like tornadoes and hurricanes. Doppler radar can not only see rain and snow forming inside a cloud but can also 'see' the winds inside storms.

But even with high-tech equipment, making weather forecast is a complex business, partly because it involves a very large number of variables and also because the variables keep changing all the time. For example, for making a reasonably accurate forecast, the meteorologist needs to know the air temperature, air pressure, wind direction and velocity, and air moisture content at any instant at several hundred

locations simultaneously, which itself is a colossal task. Processing such huge volumes of data in real time needs the power of supercomputers.

Today all weather forecasts are based on numerical weather prediction models, which are computer simulations of the atmosphere. The collected data are analysed and used as the starting point to predict the state of the atmosphere in a future time using understanding of physics and fluid dynamics. The complicated equations which govern how the state of a fluid changes with time require supercomputers to solve them. Once the data are fed into them the computers can make forecasts based on the numerical model, and display them on weather maps. Meteorologists read the weather maps, and by interpreting the data that appears on them, they are able to make a forecast.

Medium-range forecasting

Usually weather forecasts are made for the next 24 or 48 hours. A forecast of weather conditions for a period of 48 hours to a week in advance is termed as a 'medium-range forecast'. Medium-range weather forecasting is a more complicated way of making a forecast. Broadly speaking, it makes use of a previous weather event which is expected to be mimicked by an upcoming event. What makes it a difficult technique to use is that there is rarely a perfect analog for an event in the future. Some call this type of forecasting 'pattern recognition', which nevertheless remains a useful method for forecasting of precipitation amounts and distribution in the future.

Medium-range forecasts predict the behaviour of the atmosphere in the medium-range up to ten days ahead. It is quite possible that in this time the future state of the atmosphere at any point is influenced by phenomena at very

distant geographical locations. To give a simple example, let us suppose raindrops falling onto the top of the Andes Mountains in South America encounter a light easterly breeze. The rain will then be blown onto the western side of the mountain, eventually reaching the Pacific Ocean and interacting with weather systems there. But if there is a gentle westerly wind the raindrops will fall onto the eastern side and eventually become part of the Atlantic Ocean weather systems. There may be similar uncertainties that can totally change the course of predicted weather. Such uncertainties often reduce the reliability of medium-range weather forecasts.

Although this is still the case today, weather prediction has been transformed through the implementation of what meteorologists call 'ensemble forecasts'. To cater for the very small change in the initial position of the raindrops mentioned above, ensemble forecasts run the deterministic forecast many times using slightly different starting points ending up with many different forecasts for a few days ahead.

An ensemble forecast comprises multiple (typically between 5 and 100) runs of numerical weather prediction models, which differ in the initial conditions and/or the numerical representation of the atmosphere, thereby addressing the two major sources of forecast uncertainty. If the results for most of the forecasts are very similar for a certain point in time, then the meteorologist has a high degree of confidence in the forecast. If, on the other hand, the ensemble forecast has a wide scattering of results, then the confidence in a particular forecast is much lower.



Weather forecasting in India

The beginnings of meteorology in India can be traced to ancient times. Early philosophical writings of the 3000 B.C., such as the *Upanishadas*, contain serious discussion about the processes of cloud formation and rain and the seasonal cycles caused by the movement of Earth round the Sun. Varahamihira's classical work, the *Brihatsamhita*, written around A.D. 500, provides clear evidence that a deep knowledge of atmospheric processes existed even in those times. It was understood that rains come from the Sun (*adityat jayate vrishti*) and that good rainfall in the rainy season was the key to bountiful agriculture and food for the people. Kautilya's *Arthashastra* contains records of scientific measurements of rainfall and its application to the country's revenue and relief work. Kalidasa in his epic, *Meghdoot*, written around the seventh century, even mentions the date of onset of the monsoon over central India and traces the path of the monsoon clouds.

Some of the oldest meteorological observatories of the world were established in India in the late 1700s. These include the observatories at Calcutta (now Kolkata) in 1785 and

Madras (now Chennai) in 1796 for studying the weather and climate of India. The India Meteorological Department (IMD) was established in 1875 after a disastrous tropical cyclone struck Calcutta in 1864 and the failure of the monsoon rains in 1866 and 1871. With the establishment of IMD all meteorological work in the country was brought under a central authority. The first Director General of Observatories was Sir John Eliot who was appointed in May 1889 at Calcutta headquarters. The headquarters of IMD were later shifted to Shimla, then to Poona (now Pune), and finally to New Delhi.



The headquarters of IMD in New Delhi.

The early pioneers

In view of the importance of monsoon seasonal rainfall for the agricultural economy of the country, a system of Long Range Forecasting (LRF) was introduced by H. F. Blanford, who was appointed Meteorological Reporter to the Government of India. The system of LRF of monsoon rains went through several evolutionary phases and eminent

pioneers like Sir J. Eliot and Sir Gilbert Walker, and generations of Indian researchers made their contributions to this scientific effort.

To Sir Gilbert Walker also goes the credit of linking the Indian monsoon with global meteorological situations and his discovery of the so-called Southern Oscillation phenomenon, which reflects the monthly or seasonal fluctuations in the air pressure difference between Tahiti in South Pacific Ocean and Darwin in north-western Australia. Swings of the Southern Oscillation were later linked by J. Bjerknes with the El Niño in the equatorial Pacific Ocean and Bjerknes also coined the term 'Walker circulation' for describing the east-west vertical circulation in the equatorial plane in honour of Walker.

Blanford had recognised the need for inducting young Indians in IMD and the first two Indians – Lala Ruchi Ram Sahni (Father of Professor Birbal Sahni) and Lala Hemraj – joined IMD in 1884 and 1886 respectively. The Indianisation of IMD was accelerated under Walker, soon after World War I, and further boosted by Sir C.W.B. Normand (Director-General during 1928 to 1944). Normand was succeeded by Dr. S.K. Banerji as the first Indian Director General of Observatories in 1944. During these years, many Indian scientists joined IMD and they took IMD to greater heights themselves in the post-independence era.

From a modest beginning in 1875, IMD has progressively expanded its infrastructure for meteorological observations, communications, forecasting and weather services. The IMD has always used contemporary technology. In the telegraph age, it made extensive use of weather telegrams for collecting observational data and sending warnings. Later, IMD became the first organisation in India to have a message switching

computer for supporting its global data exchange. One of the first supercomputers in the country was provided to IMD for use in weather forecasting. India was the first developing country in the world to have its own geostationary satellite, *INSAT*, for continuous weather monitoring of this part of the globe and particularly for cyclone warning.

Forecasting monsoons

For a predominantly agricultural country like India, timely monsoon rain is crucial for food production and replenishment of water sources. The monsoon accounts for 80 percent of the rainfall in the country. Indian agriculture (which accounts for 25 percent of the GDP and employs 70 percent of the population) is heavily dependent on the rains, especially crops like cotton, rice, oilseeds and coarse grains. Success or failure of the crops and water scarcity in any year is always closely linked with the amount of the monsoon rains in India. A delay of a few days in the arrival of or insufficient rain during monsoon can, and does, badly affect the economy, as evidenced in the numerous droughts in India in the 1990s. So, reliable prediction of monsoon rainfall at least a few months in advance is of vital importance to safeguard Indian agriculture against erratic monsoons.

IMD makes use of statistical methods for making seasonal predictions of the Indian monsoon rainfall. The statistical models are based on parameters representing past records of the coupled atmosphere-ocean-land system such as Arabian Sea surface temperature, South Indian Ocean surface temperature, Indian Ocean Equatorial Pressure, Himalayan snow cover, Eurasian snow cover, and so on. The most commonly used statistical technique for seasonal prediction of monsoon rainfall is called the 'linear regression analysis'. Monsoon is the result of the contrast between land and sea

heating, which involves large-scale seasonal reversal of pressure, temperature and winds. Based on this fact many studies have been carried out to identify useful parameters that can be used for monsoon prediction based on the pressure and thermal fields during preceding winter and pre-monsoon seasons.

During the decade 1981-90, several efforts were made to develop new seasonal prediction techniques and a new 16-parameter model was found to be quite useful in predicting the seasonal rainfall. Since 1988, the long-range forecasts were issued by IMD for the country as a whole, based on the 16-parameter model. However, after successful predictions for 14 years running, the 16-parameter statistical model for the long-range forecast (LRF) of the monsoon failed enormously in 2002. It was off by 20 per cent against the claimed model error of ± 4 per cent. The model predicted a 'normal' monsoon with 101 per cent rainfall, whereas the actual rainfall was only 81 per cent. Following this, the IMD came up with entirely new models for predicting monsoon rainfall. Considering the importance of July rainfall to agriculture, a new eight-parameter power regression model for July rainfall requiring data up to June, was developed for issuing a forecast for July rainfall along with the forecast update. The revamped models permitted a forecast in mid-April itself as against the fourth week of May in the case of the earlier model. Besides, the new scheme enabled a mid-course correction in July, which could help minimise the impact of a deficient monsoon on agriculture. The new model divided the probability of the monsoon rainfall for the country as a whole into five different categories: Drought (less than 90 % of long period average); Below Normal (90 to 97 %); Near Normal (98 to 102 %); Above Normal (103 to 110 %); Excess (more than 110 %).

In 2007 the IMD introduced a new five-parameter statistical forecasting system that uses data up to March for the first forecast in April and a new six-parameter statistical model that uses data up to May for the forecast update in June for long-range forecast of southwest monsoon over the country as a whole.

Considering the importance of the summer monsoon to Indian economy, IMD is constantly updating its technique for making long-range forecasts. It has started using dynamic models for forecasting southwest monsoon rainfall. It takes help of the experimental forecasts prepared by the National Centre for Medium-Range Weather Forecast (NCMRWF), Noida, and the Indian Institute of Tropical Meteorology, Pune, using dynamic models. Hopefully, statistical models will be replaced by more reliable dynamic models at IMD in the near future for long-range forecasting of the Indian monsoon rainfall.

Glossary

Atmosphere

It is a layer of gases surrounding Earth and retained by the Earth's gravity. It contains roughly 78% nitrogen, 20.95% oxygen, 0.93% argon, 0.038% carbon dioxide, trace amounts of other gases, and a variable amount (average around 1%) of water vapour.

Cloud

A visible cluster of tiny water and/or ice particles suspended in the atmosphere.

Depression

An air mass of lower pressure, usually with high moisture content that often brings precipitation. Deep depressions, when formed over warm oceans, often turn into tropical cyclones.

Dew

As the surface of the Earth cools at night, warm moist air near the ground is chilled and water vapour in the air condenses into droplets on the grass and other objects. Dew is particularly heavy on clear nights.

Dew point

It is the temperature to which air must be cooled to become saturated by the water vapour already present in the air. The warmer the air, the more moisture it can hold.

Fog

Fog is cloud at ground level, and occurs when air is cooled to its dew point and below, or when atmospheric moisture increases through evaporation from water that is warmer than the air.

Front

An atmospheric phenomenon created at the boundary between two different air masses.

Frost

Frost is water vapour which deposits directly as a solid on a surface colder than the surrounding air and which has a temperature below freezing. It is not frozen dew. A killing frost is a frost severe enough to destroy annual plants and new growth on trees.

Global warming

Global warming refers to the increase in the average temperature of the Earth's near-surface air and oceans in recent decades due to increase in the level of greenhouse gases like carbon dioxide and methane in the atmosphere.

Greenhouse effect

A general warming of the air inside a greenhouse due to trapping of radiated heat by the glass roof and walls of the greenhouse. A similar effect is created by gases like carbon dioxide and water vapour in Earth's atmosphere, which trap

the heat radiated by the Sun-heated Earth's surface leading to global warming.

Humidity

The amount of moisture in the air. Relative humidity is the ratio of water vapour in the air at a given temperature to the maximum amount which could exist at that temperature. On hot summer days, the higher the relative humidity, the greater the discomfort, since perspiration evaporates less readily and the body feels more hot and sticky.

Inversion

It is a deviation from the normal change of an atmospheric property with altitude. It almost always refers to a temperature inversion, i.e., an increase in temperature with height, contrary to a decrease in temperature that is normal.

Isobar

A line on a map connecting points having equal barometric pressure at a given time.

Isohyet

A line joining locations of equal precipitation on a map.

Jet streams

These are undulating bands of strong, high-altitude winds, associated with cold fronts. They have an average altitude of 10 km and may occasionally exceed 400 km/h. Pilots often seek out a jet stream to speed their jet planes along.

Precipitation

Condensation of atmospheric water vapour deposited on the Earth's surface. It occurs when airborne water droplets

become too heavy for the air to support any longer. The moisture can fall as rain, snow, ice pellets or hail, depending on the air temperature and currents.

Radiosonde

Radiosonde is a small instrument package to measure temperature, humidity, and air pressure that is carried into the upper atmosphere by balloon. As it travels upward, it transmits meteorological measurements to ground stations.

Storm surge

Storm surge is the rising of the sea level due to the low pressure, high winds, and high waves associated with a tropical cyclone as it makes landfall. The storm surge can cause significant flooding and cost people their lives if they are caught unawares.

Wind

Wind is the horizontal movement of air relative to the Earth's surface and is caused by variations in temperature and pressure. The wind direction is the direction from which the wind is blowing.

Wind chill

It is the apparent temperature felt on exposed skin due to the combination of air temperature and wind speed. The wind chill temperature (often popularly called the 'wind chill factor') is always lower than the air temperature.

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